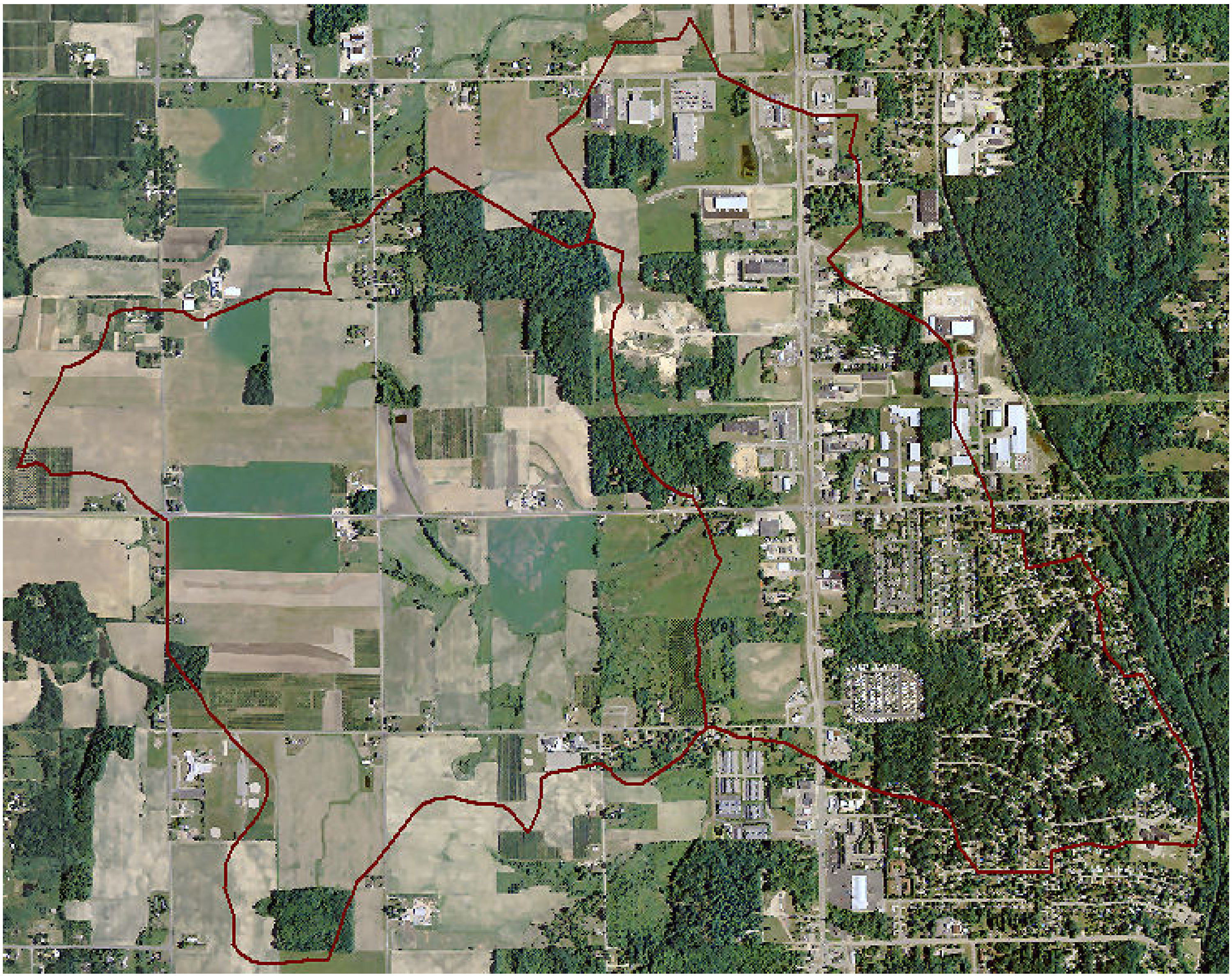
Strawberry Creek Watershed Hydrologic Study



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DEQ
Michigan's Nonpoint Source Program

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This Nonpoint Source (NPS) Pollution Control project has been funded wholly by the United States Environmental Protection Agency (EPA) through a Part 319 grant to the Michigan Department of Environmental Quality. This study is in support of a NPS grant, 2007-0137, to the Grand Valley Metropolitan Council. The contents of the document do not necessarily reflect the views and policies of the EPA, nor does the mention of trade names or commercial products constitute endorsement or recommendation for use. For more information, go to www.michigan.gov/deqnps.

The cover is a 2005 aerial photo of the Strawberry Creek Watershed.

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DEQ Michigan's Nonpoint Source Program

Summary

This hydrologic study of the Strawberry Creek watershed was conducted by the Hydrologic Studies Unit (HSU) of the Michigan Department of Environmental Quality (MDEQ) to better understand the watershed's hydrologic characteristics and reported continued channel instability subsequent to a streambank stabilization project. The project also supports a task in the Lower Grand River Watershed Initiatives NPS grant to review channel protection criteria in the lower Grand River watershed and improve watershed-specific guidance to protect channel morphology based on nationally accepted criteria.

The watershed study has six scenarios, Table 1, corresponding to land cover in 1800, 1978, 2006, and built-out as shown on the 2007 Alpine Township Future Land Use map. General land use trends for the watershed are illustrated in Figure 1. Additional land use information is provided in the Watershed Description section of this report.

Table 1 – Hydrologic Model Scenarios

Scenario	Land Cover	Channel Protection Stormwater Management, New Development
A	1800	None
B	1978	None
C	2006	None
D		0.05 cfs/acre release rate*
E	Build-out	None
F		0.05 cfs/acre release rate*

* Requirement of Alpine Township stormwater management ordinance

The hydrologic modeling quantifies changes in stormwater runoff from 1800 through 1978 and 2006 and into the future due to land use changes. The dominant trend from 1978 to 2006 and into the future is urbanization, especially of the lower watershed, and increased imperviousness. The associated increased runoff is managed by Alpine Township's stormwater ordinance. For recent and new developments, runoff from a 50 percent chance (2-year), 24-hour storm event is limited to a maximum release rate of 0.05 cubic feet per second per acre (cfs/acre). Relatively modest, but frequent, storm events, such as the 50 percent chance storm, have more effect on channel form than extreme flood flows. Unless properly managed, increases in runoff from 1- to 2-year storms increase channel-forming flows, which increase streambank and bed erosion as the stream enlarges to accommodate the higher flows. Detailed discussion of the results is in the Hydrologic Analysis section of this report.

The modeling indicates that the 0.05 cfs per acre channel protection requirement in the Alpine Township stormwater management ordinance is helping moderate, but does not eliminate, detrimental flow impacts of land use changes in Strawberry Creek. Channel-forming flows near the mouth of Strawberry Creek have significantly increased and will continue to increase with future development within the watershed. The duration of the erosive flows will also increase. Refinements to the stormwater ordinance would help better protect Strawberry Creek. These refinements could include 24-hour extended detention of runoff from 1-year storms or provision for retention and infiltration of additional stormwater runoff through Low Impact Development (LID) practices.

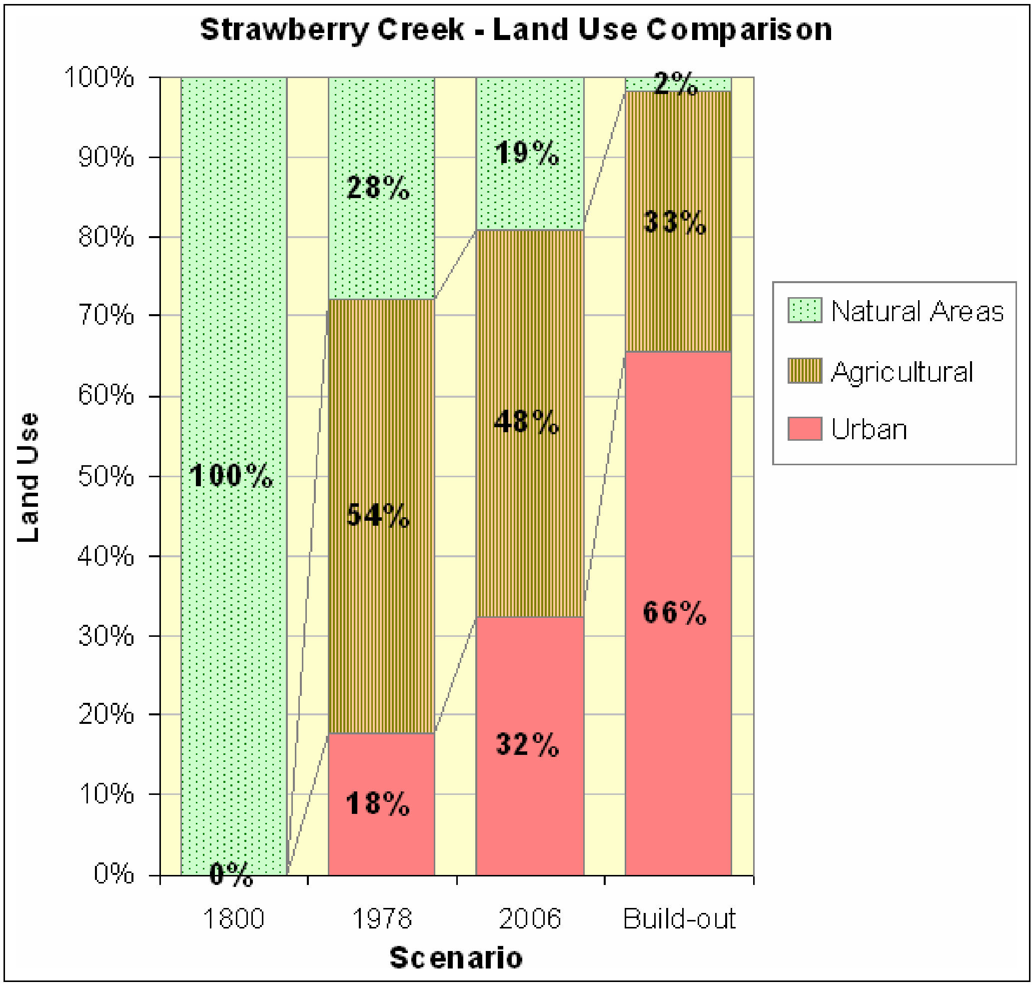

Figure 1: Land Use Comparison, Strawberry Creek Watershed

Watershed Description

The 3.0 square mile Strawberry Creek watershed, Figure 2, outlets to Mill Creek two miles from its confluence with the Grand River at Comstock Park in Kent County. Streambank stabilization project sites are located in Westgate Park, slightly upstream of the mouth. Strawberry Creek is a designated trout stream.

This study divides the watershed into two subbasins, as shown in Figure 3. Surface runoff volumes and flows were modeled using HEC-HMS 3.1.0 and the runoff curve number technique. This technique, developed by the Natural Resources Conservation Service (NRCS) in 1954, represents the runoff characteristics from the combination of land use and soil data as a runoff curve number. The technique, as adapted for Michigan, is described in “Computing Flood Discharges For Small Ungaged Watersheds (Sorrell, 2003).

The runoff curve numbers were calculated using Geographic Information Systems (GIS) technology from the digital land use and soil data shown in Figures 4 through 8. The land use maps depicting MDEQ GIS data for 1800 and 1978 are shown in Figures 4 and 5 respectively. The 2006 land use map, Figure 6, is based on HSU's analysis of 2005 and 2006 aerial photos. The build-out land use map, Figure 7, is based on the 2007 Alpine Township Future Land Use map. Housing density is a part of the curve number calculations. Based on the aerial photos, average residential lot size for all land use scenarios was specified as 1 acre in the upper watershed and 1/2 acre for the lower watershed.

Table A1: Land Use by Subbasins

Description	Scenario	Residential	Commercial	Industrial	Gravel Pit	Cemeteries, Outdoor Rec.	Cropland	Orchards	Pasture	Herbaceous Openland	Forest	Water	Wetland	Bare Soil
Upper	1800										98.8%		1.2%	
	1978	1.4%	0.7%			0.4%	62.6%	18.3%	0.8%	5.1%	10.7%	0.1%		
	2006	5.1%	0.7%		0.5%	1.2%	70.4%	8.8%	0.4%	3.1%	9.8%	0.1%		
	Build-out	36.5%	0.7%	2.6%		1.2%	51.7%	6.9%	0.4%			0.1%		
Lower	1800										100%			
	1978	27.0%	5.8%	3.5%	0.3%		18.5%	2.5%		23.0%	17.9%		1.5%	
	2006	33.1%	16.2%	9.8%	3.4%		9.6%	1.1%		11.3%	13.5%		1.8%	0.3%
	Build-out	42.9%	22.0%	30.4%			0.8%			0.1%	3.4%		0.4%	
Entire Watershed	1800										99.3%		0.7%	
	1978	13.0%	3.0%	1.6%	0.2%	0.2%	42.6%	11.2%	0.5%	13.2%	13.9%		0.7%	
	2006	17.8%	7.7%	4.4%	1.8%	0.6%	42.8%	5.3%	0.2%	6.8%	11.4%		0.8%	0.1%
	Build-out	39.4%	10.3%	15.2%		0.6%	28.7%	3.8%	0.2%	0.1%	1.5%		0.2%	

The NRCS soils data for the watershed is shown in Figure 8. Soil hydrogroups range from A to D, with A indicating well-drained, high infiltration soils and D indicating poorly-drained, high runoff soils. Where the soil is given a dual classification, B/D for example, the soil hydrogroup was selected based on land use. In these cases, the soil hydrogroup is specified as D for natural land uses, or the alternate hydrogroup (A, B, or C) for developed land uses. The runoff curve numbers, calculated from the soil and land use data, are listed in Appendix A.

The developed areas that are affected by the 0.05 cfs/acre standard in the 2006 and build-out scenarios were modeled as separate elements. An impervious area for each of these developed areas was assigned based on the land use GIS data, Figures 6 and 7, and Table 2. The imperviousness values for residential, commercial, and industrial land uses are from the NRCS (NRCS, 1986). The pervious portion of the drainage area was assigned a curve number of 45.

Table 2: Imperviousness Table for Impervious Area Analysis

GIS Class	Description	Imperviousness (percent)
1	Residential	38*
2	Commercial	85
3	Industrial	72
4	Road, Utilities	95
5	Gravel Pits	0
6	Outdoor Recreation	0
7	Cropland	0
8	Orchard	0
9	Pasture	0
10	Openland	0
11	Forests	0
12	Open Water	0
13	Wetland	0

* assumed population density of 250 to 1,000 people per square mile

The time of concentration, which is the time it takes for water to travel from the hydraulically most distant point in the watershed to the design point, was calculated from the USGS quadrangles. The same time of concentration values were used in all land use scenarios. Storage coefficients were set equal to the times of concentration because there is little ponding within the watershed. Parameters are detailed in Appendix A.

The design rainfall value used in this study is 2.37 inches, corresponding to the 50 percent chance (2-year) 24-hour storm, as tabulated in *Rainfall Frequency Atlas of the Midwest*, Bulletin 71, Midwestern Climate Center, 1992, pp. 126-129. This storm was selected because runoff from the 50 percent chance storm approximates channel-forming flows.

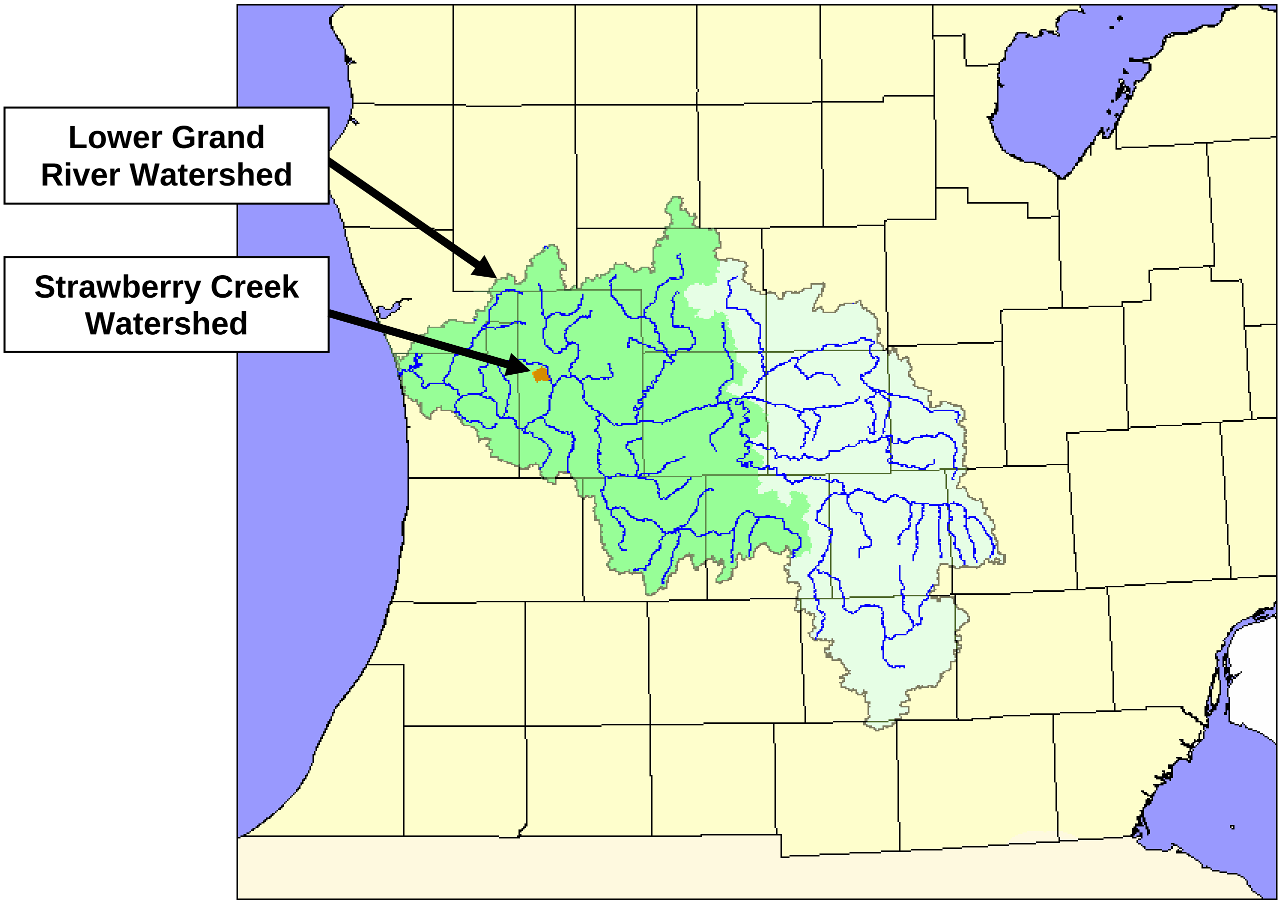

Figure 2: Strawberry Creek Watershed Location

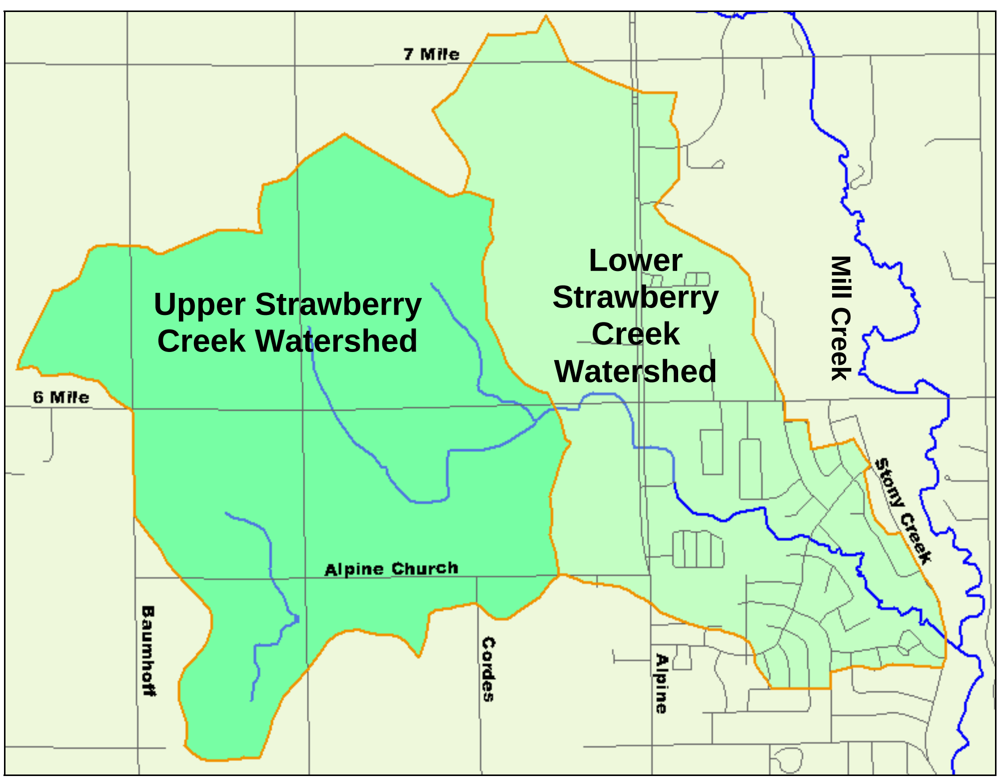

Figure 3: Strawberry Creek Subbasin Identification

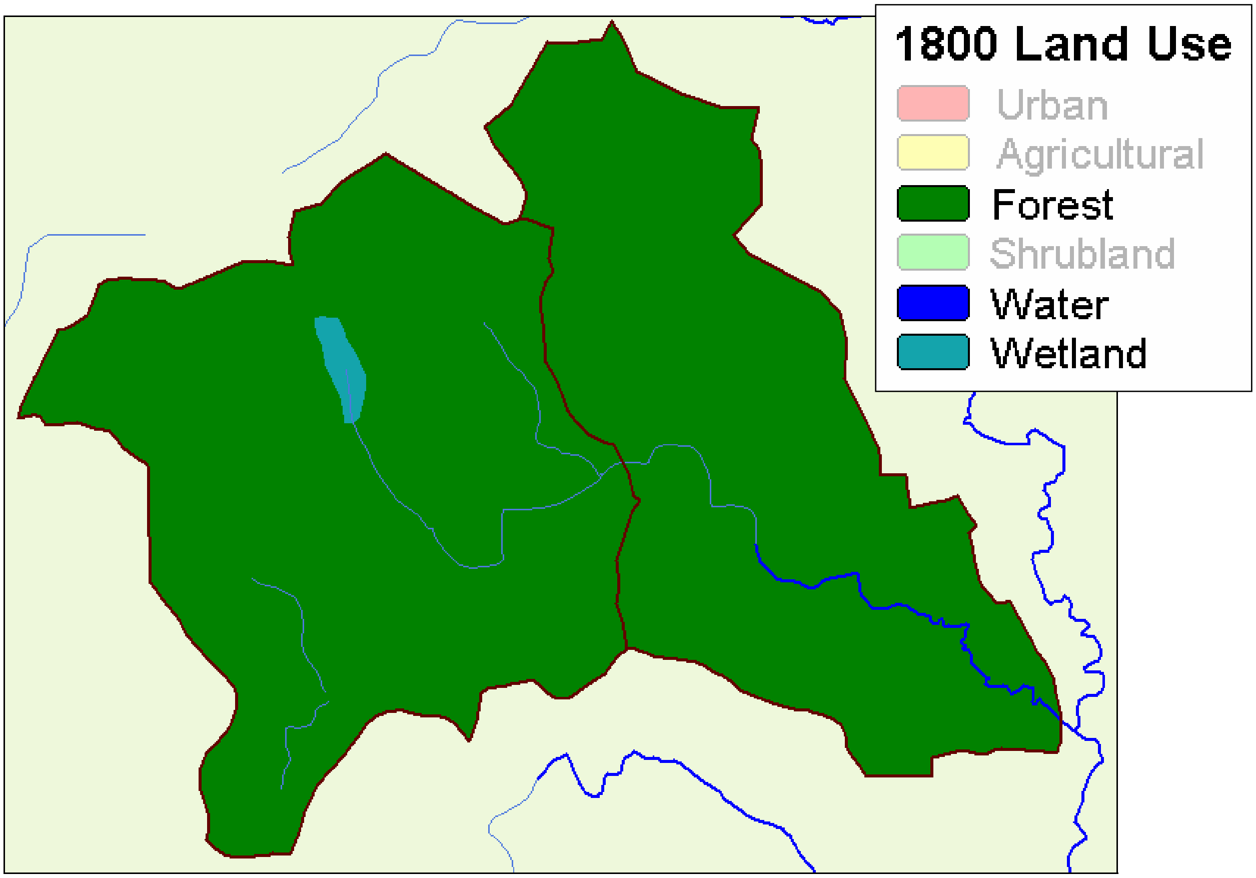

Figure 4: 1800 Land Cover

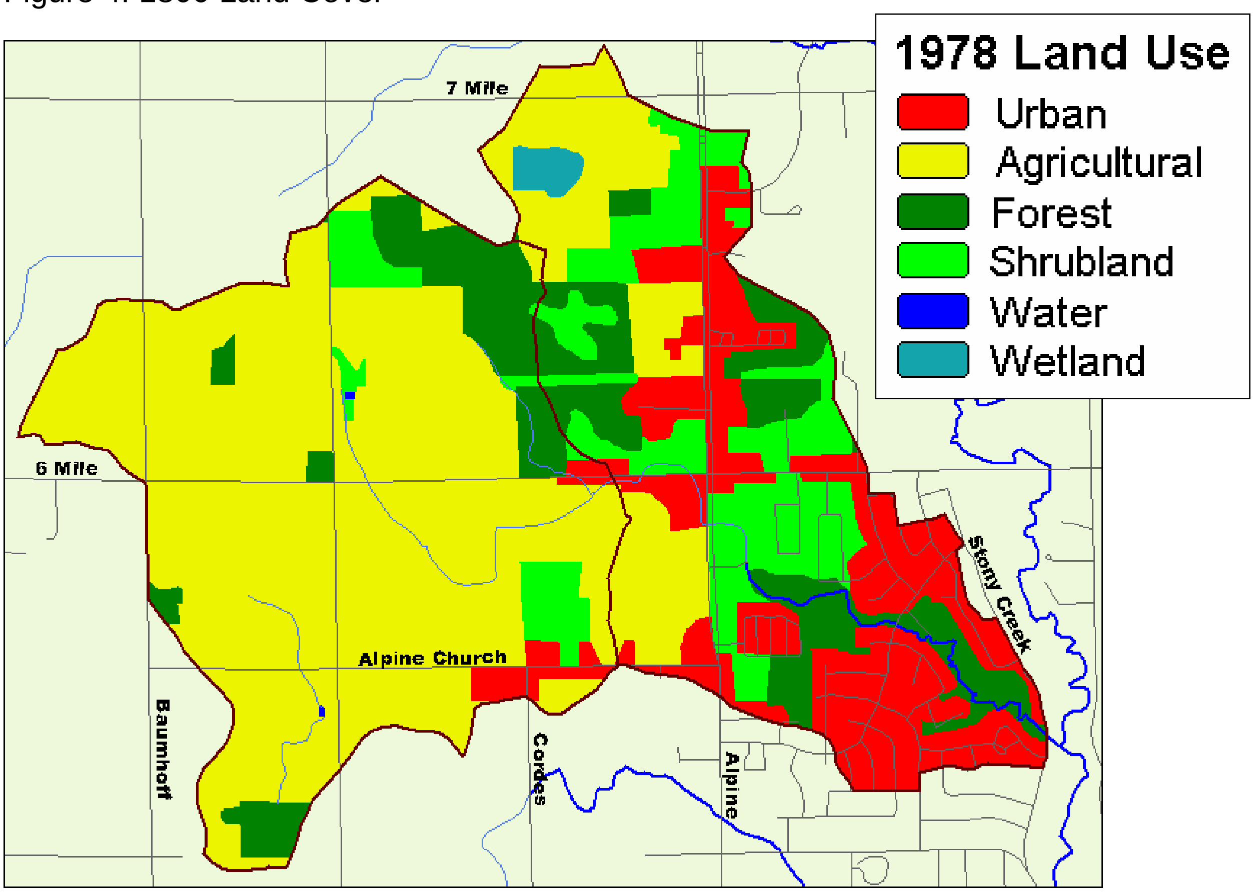

Figure 5: 1978 Land Cover

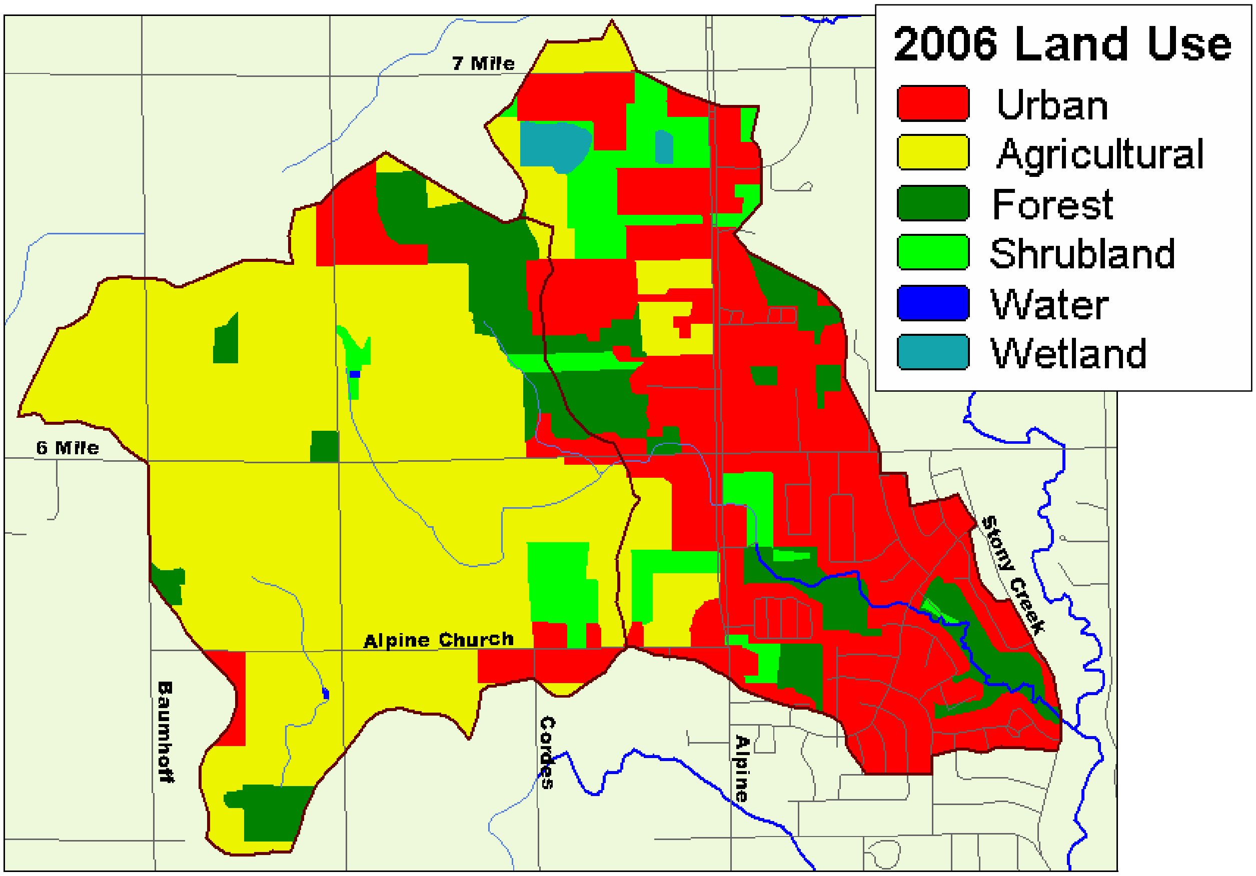

Figure 6: 2006 Land Cover

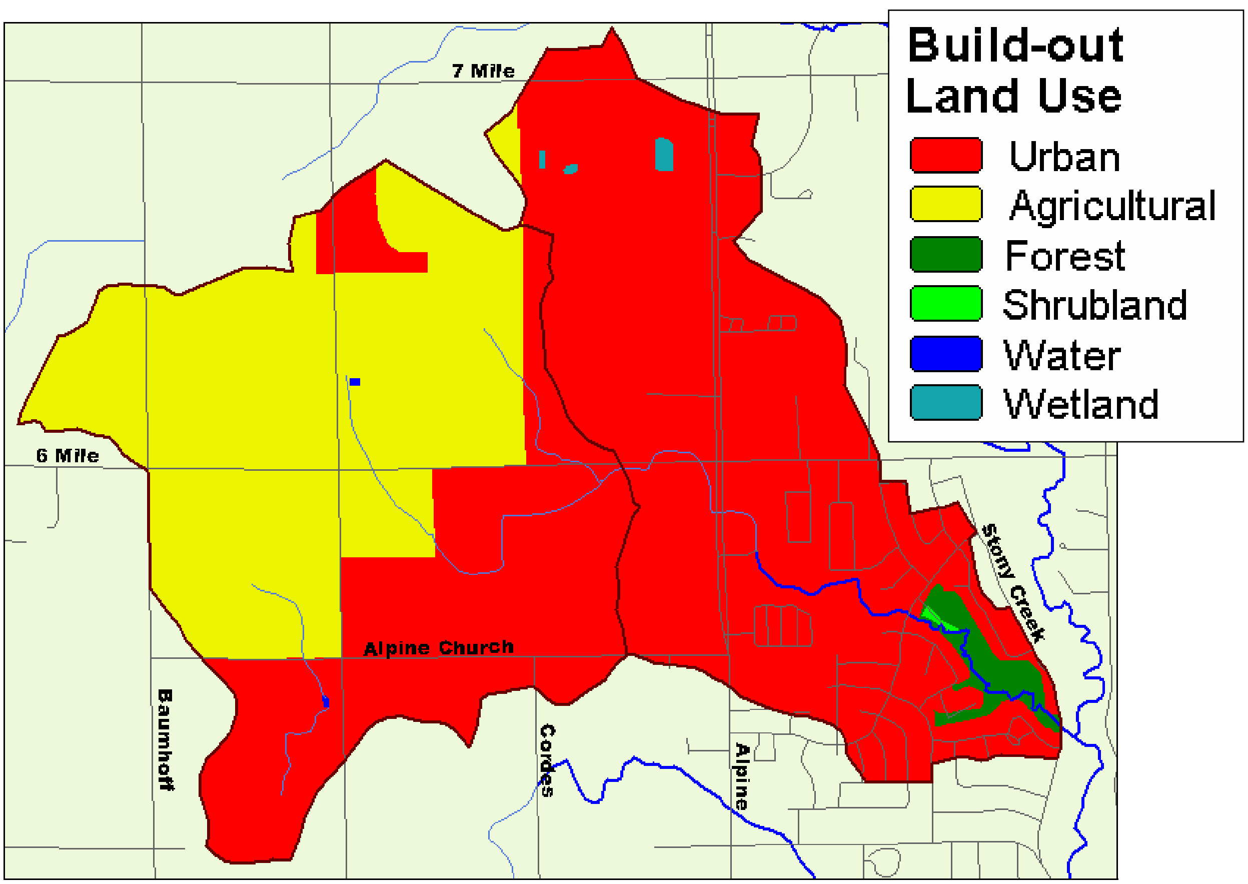

Figure 7: Build-out Land Cover

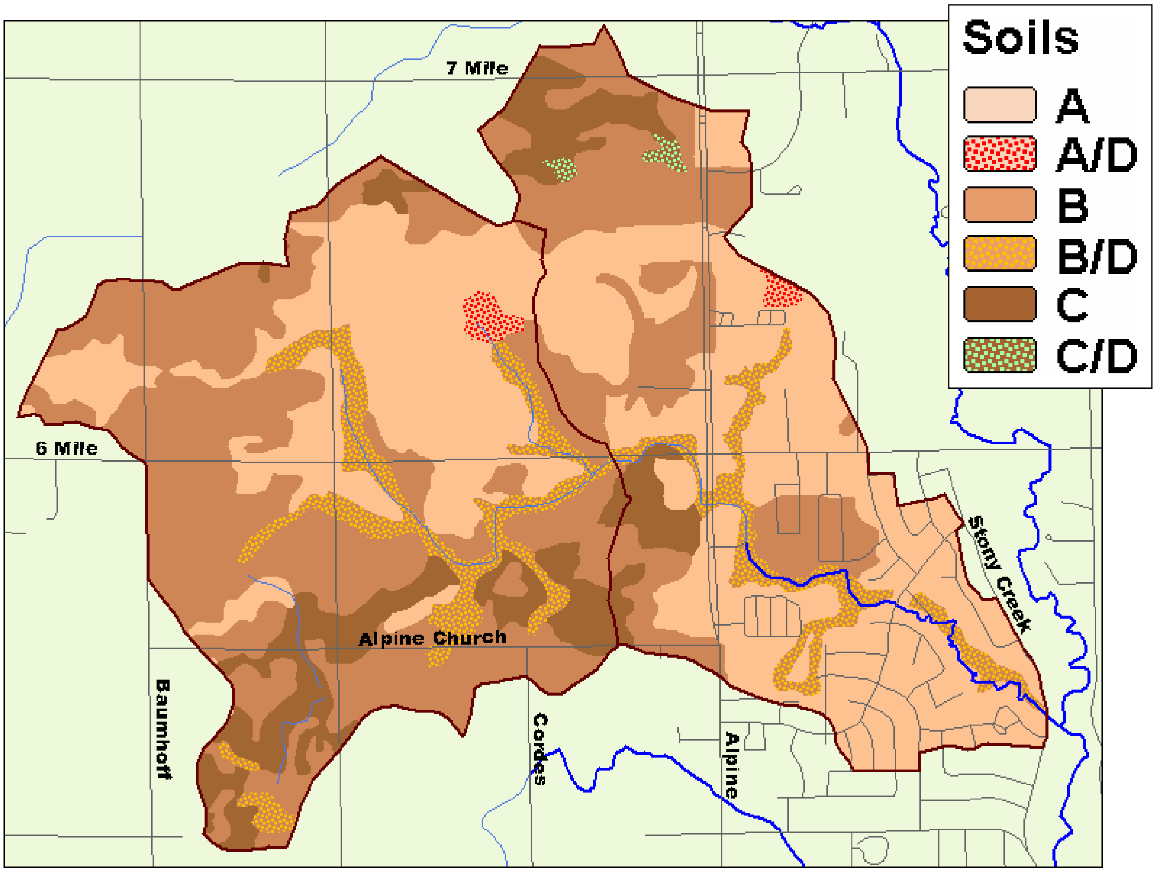

Figure 8: NRCS Soils Data

Hydrologic Analysis

General

The impetus for this study was whether recent hydrologic changes are adversely affecting Strawberry Creek's morphology, which is the form and structure of its channel. Channels are shaped primarily by flows that recur fairly frequently; every one to two years in a stable stream. Increases in runoff volumes and peak flows from 1- to 2-year storms increase channel-forming flows, which causes more streambank and bed erosion as the stream enlarges to accommodate the higher flows. This study is therefore focused on model results from the 50 percent chance (2-year), 24-hour storm. The modeled precipitation event is shown in Figures 10 and 11, displayed in inches per hour for clarity.

The primary hydrologic change in the watershed since 1978 is urbanization and the associated increased imperviousness in the lower watershed. To protect streams from increased erosion, a local stormwater ordinance mandates that new developments release runoff from a 50 percent chance, 24-hour storm event at a maximum rate of 0.05 cfs/acre.

The watershed study has six scenarios, Table 3, corresponding to land cover in 1800, 1978, 2006, and build-out as shown on the 2007 Alpine Township Future Land Use map. Scenarios A, B, and D simulate the actual condition of the watershed at that time. Scenario F is intended to model the watershed in the future with current land use management standards. Scenarios C and E model the watershed with no stormwater management standards and are provided for comparison only. The 0.05 cfs/acre release rate requirement was applied to newly developed areas in the 2006 and build-out scenarios, as shown in Figure 9. The 0.05 cfs/acre release rate requirement was not applied to newly developed low-density residential areas. New development was assumed to not alter the boundary between the upper and lower watersheds. Redevelopment was not considered, although if an area were redeveloped, it would probably be required to meet current stormwater management standards.

Table 3 – Hydrologic Model Scenarios

<table>
<tr><th>Scenario</th><th>Land Cover</th><th>Channel Protection Stormwater Management, New Development</th></tr>
<tr><td>A</td><td>1800</td><td>None</td></tr>
<tr><td>B</td><td>1978</td><td>None</td></tr>
<tr><td>C</td><td rowspan="2">2006</td><td>None</td></tr>
<tr><td>D</td><td>0.05 cfs/acre release rate*</td></tr>
<tr><td>E</td><td rowspan="2">Build-out</td><td>None</td></tr>
<tr><td>F</td><td>0.05 cfs/acre release rate*</td></tr>
</table>

* Current requirement of Alpine Township stormwater management ordinance

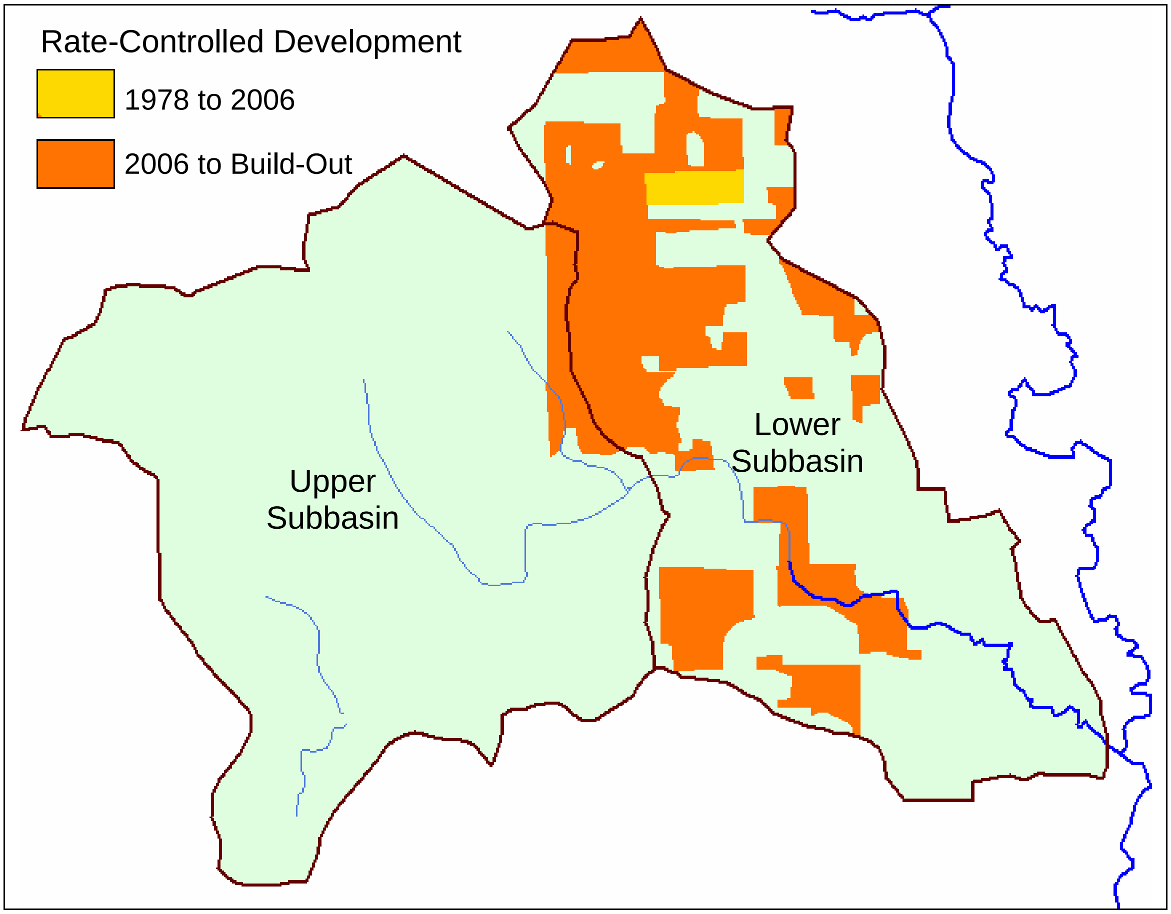

Figure 9: Modeled Rate-Controlled Development

Model Assumptions

An assumption of the runoff curve number technique is that the entire watershed contributes runoff. The curve number technique documentation is the NRCS's Part 630 Hydrology National Engineering Handbook. Chapter 10, Section 630-1003 Accuracy, of this handbook states, "The runoff equation generally did reasonably well where the runoff was a substantial fraction of the rainfall, but poorly in cases where the runoff was a small fraction of the rainfall; i.e., the CNs are low or rainfall values are small. Curve numbers were originally developed from annual flood flows from experimental watersheds, and their application to low flows or small flood peak flows is not recommended. (See Hawkins, et al. 1985, for a precise measure of small.)" According to Hawkins, "relative storm size is then proposed to be defined on the ratio P/S, where a "large" storm has P/S>0.46, when 90 percent of all rainstorms will create runoff." P/S is the ratio of precipitation, P, to potential maximum retention, S. When P/S is less than 0.46, runoff volumes and peak flows for smaller events would depend upon the portion of each subbasin contributing runoff, which will vary with the rainfall total and intensity.

Several of the results do not meet the P/S test, Table 4, meaning only a portion of a subbasin may be contributing runoff, not the entire subbasin as assumed in the model. Because the 1800 land cover was practically uniform, this author suggests that the model results for the upper and lower subbasins, 1800 scenario are valid.

The lower subbasin results, 1978 and 2006 scenarios, also do not meet the P/S ≥ 0.046 test, although the 2006 scenario is only 0.01 too low. Because of the varied land cover in the lower watershed, these results may underestimate peak flow and runoff volume, which is generated more quickly from directly connected impervious areas in smaller rain events.

Table 4 – Model results that do not meet the P/S ≥ 0.46 test

<table>
<tr><th>Watershed</th><th>Scenario</th><th>P/S</th></tr>
<tr><td>Upper</td><td>1800</td><td>0.35</td></tr>
<tr><td rowspan="3">Lower</td><td>1800</td><td>0.28</td></tr>
<tr><td>1978</td><td>0.36</td></tr>
<tr><td>2006</td><td>0.45</td></tr>
</table>

Results – Upper Watershed

Table 5 and Figure 10 show the 50 percent chance storm results for the upper Strawberry Creek watershed. The model indicates that runoff volumes and peak flows increased substantially from 1800 to 1978, seven to eleven percent from 1978 to 2006, and should be basically stable in the future with current stormwater management requirements, although runoff volume is projected to increase by another four percent. Without the requirements, the model predicts a five percent higher peak flow.

These flows could be measured by a gage at the downstream end of the subbasin. If a stream gage were installed at this location, the flow changes from 1978 to 2006 should have been detectable above natural variation.

Table 5 – Results: Upper Watershed Subbasin

<table>
<tr><th>Model Scenario</th><th>Runoff Volume (acre-feet)</th><th>Change</th><th>Peak Flow (cfs)</th><th>Change</th></tr>
<tr><td>1800</td><td>*11.0</td><td></td><td>*11</td><td></td></tr>
<tr><td>1978</td><td>32.1</td><td>From 1800: +190%</td><td>38</td><td>From 1800: +250%</td></tr>
<tr><td>2006</td><td>34.3</td><td>From 1978: +7%</td><td>42</td><td>From 1978: +11%</td></tr>
<tr><td>Build-out, with Rate Control</td><td rowspan="2">35.7</td><td rowspan="2">From 2006: +4%</td><td>40</td><td>From 2006: -5%</td></tr>
<tr><td>Build-out, no Rate Control</td><td>44</td><td>From 2006: +5%</td></tr>
</table>

* Results may be inaccurate; P/S value is below 0.46; see Model Assumptions section.

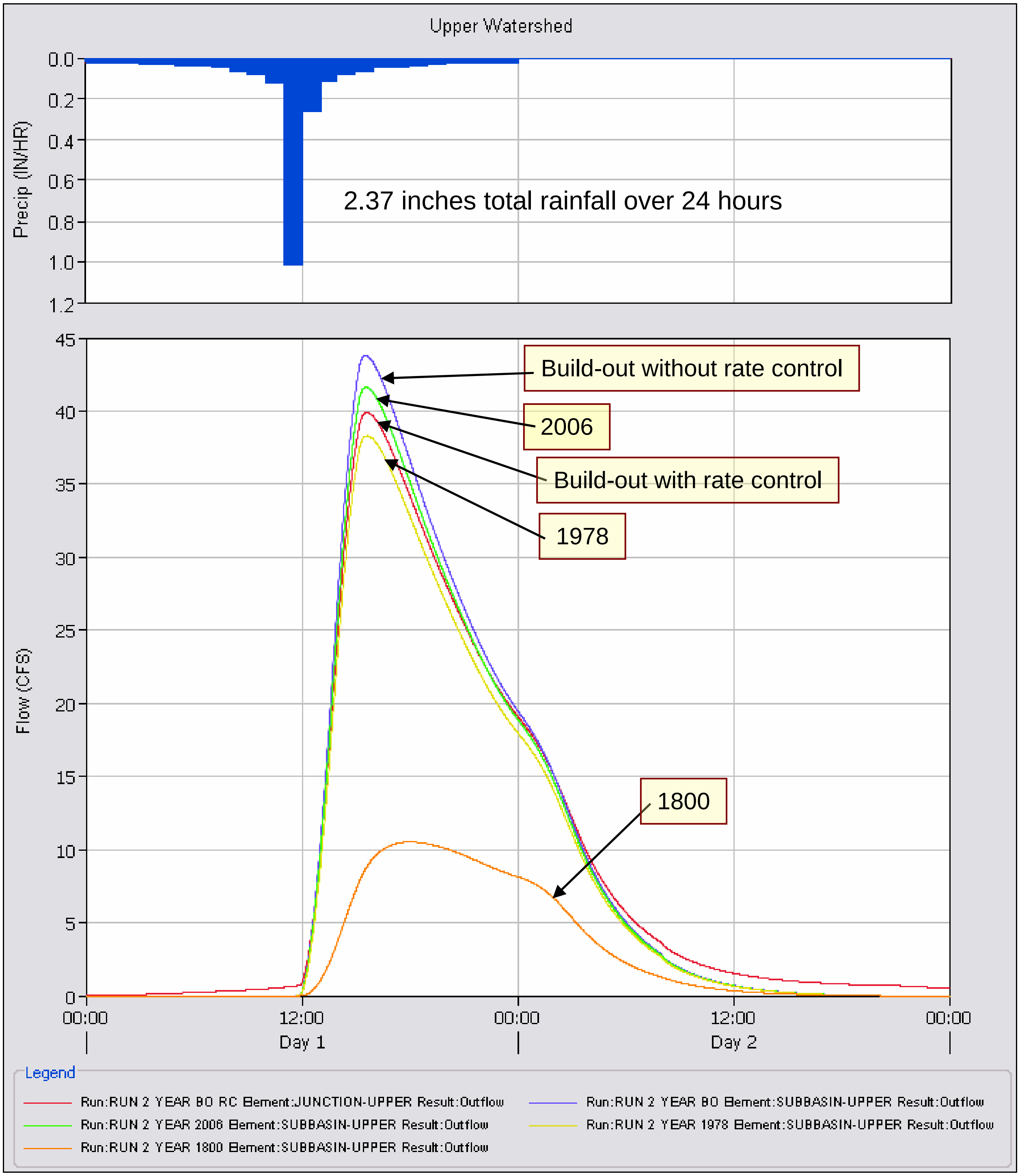

Figure 10: Hydrographs for Upper Strawberry Creek Watershed Subbasin

Results – Lower Watershed Subbasin

Table 6 shows the 50 percent chance storm results for the lower Strawberry Creek watershed subbasin. The model indicates that runoff volumes and peak flows increased substantially from 1800 to 1978 and from 1978 to 2006 and are likely to continue to increase substantially in the future. Increases in peak flow would be greater without the current stormwater management requirements.

These flows cannot be directly measured by a gage, because any in-stream measurements would also include runoff from the upper watershed. The results in Table 6 are the contribution to in-stream flows from the lower watershed. The effect on stream flow will be discussed further in the Results – Strawberry Creek at Mouth section.

Table 6 – Results: Lower Watershed Subbasin

<table>
<tr><th>Model Scenario</th><th>Runoff Volume (acre-feet)</th><th>Change</th><th>Peak Flow (cfs)</th><th>Change</th></tr>
<tr><td>1800</td><td>*3.9</td><td></td><td>*4</td><td></td></tr>
<tr><td>1978</td><td>*10.9</td><td>From 1800: +180%</td><td>*11</td><td>From 1800: +180%</td></tr>
<tr><td>2006, with Rate Control</td><td rowspan="2">*20.5</td><td rowspan="2">From 1978: +88%</td><td>*23</td><td>From 1978: +110%</td></tr>
<tr><td>2006, no Rate Control</td><td>*25</td><td>From 1978: +130%</td></tr>
<tr><td>Build-out, with Rate Control</td><td rowspan="2">57.6</td><td rowspan="2">From 2006: +180%</td><td>39</td><td>From 2006: +70%</td></tr>
<tr><td>Build-out, no Rate Control</td><td>90</td><td>From 2006: +290%</td></tr>
</table>

* Results may be inaccurate; P/S value is below 0.46; see Model Assumptions section.

Results – Strawberry Creek at Mouth

The effect of hydrologic change in one area of the watershed would normally diminish as the flows move downstream. Both the increasing variety of land uses expected with increasing drainage area and the varied timing of tributary flows adding to the main channel flow as the water flows downstream help attenuate peak flows. Thus the substantial increases estimated for the lower watershed subbasin from 1978 to 2006 and into the future are apparent in the in-stream results, but are attenuated somewhat.

Table 7 and Figure 11 show the 50 percent chance storm results for Strawberry Creek at its mouth. Because both the upper and lower watershed subbasins had substantial increases in runoff volumes and peak flows, in-stream flows at the mouth are also modeled to have increased substantially during this period. From 1978 to 2006, runoff volumes and peak flows increased 26 to 28 percent. The current 0.05 cfs/acre stormwater management requirement modeled for one development does reduce modeled peak flow for this period. In the future, runoff volume is projected to increase another 70 percent, although peak flow would increase much less, 20 percent, with current stormwater management requirements. Increases in peak flow would be greater without the current stormwater management requirements.

These flows could be measured by a gage at the mouth of Strawberry Creek. If a stream gage were installed at this location, all of these flow changes would be detectable above natural variation.

Table 7 – Results: Strawberry Creek at Mouth

<table>
<tr><th>Model Scenario</th><th>Runoff Volume (acre-feet)</th><th>Change</th><th>Peak Flow (cfs)</th><th>Change</th></tr>
<tr><td>1800</td><td>*14.9</td><td></td><td>*14</td><td></td></tr>
<tr><td>1978</td><td>*43.0</td><td>From 1800: +190%</td><td>*50</td><td>From 1800: +260%</td></tr>
<tr><td>2006, with Rate Control</td><td rowspan="2">*54.8</td><td rowspan="2">From 1978: +27%</td><td>*63</td><td>From 1978: +26%</td></tr>
<tr><td>2006, no Rate Control</td><td>*64</td><td>From 1978: +28%</td></tr>
<tr><td>Build-out, with Rate Control</td><td rowspan="2">93.4</td><td rowspan="2">From 2006: +70%</td><td>77</td><td>From 2006: +20%</td></tr>
<tr><td>Build-out, no Rate Control</td><td>113</td><td>From 2006: +77%</td></tr>
</table>

* Results may be inaccurate; P/S value is below 0.46; see Model Assumptions section.

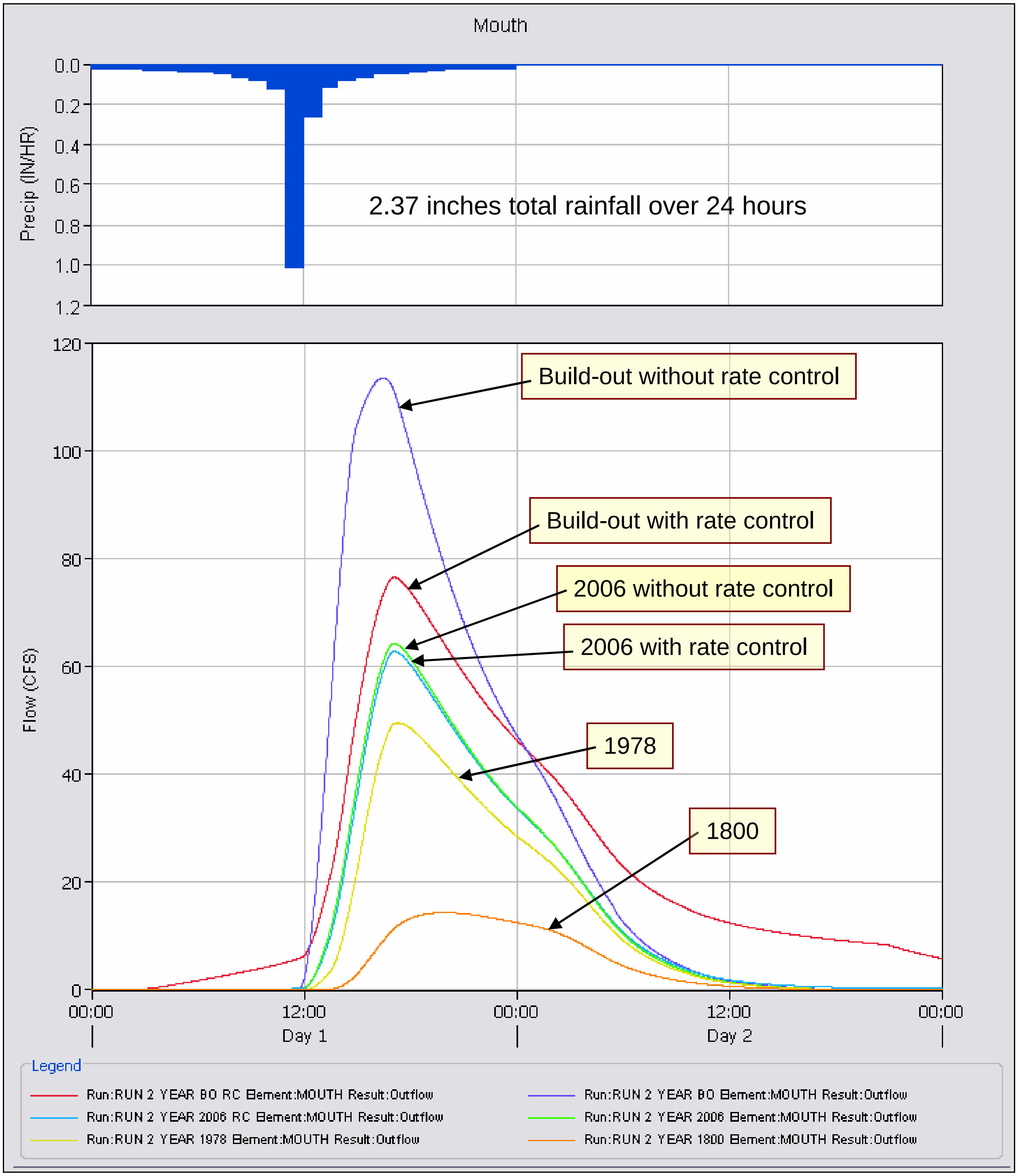

Figure 11: Hydrographs for Strawberry Creek at its mouth

Results – Effects of 24-Hour Extended Detention

Stormwater management for stream channel protection has continued to advance since the 0.05 cfs/acre standard was adopted in the Kent County model ordinance and by Alpine Township. One option is 24-hour extended detention, meaning runoff that enters a detention pond is released on average 24 hours later. To accomplish this, the release rate would generally, if not always, be lower than the current 0.05 cfs/acre requirement.

When 24-hour extended detention is applied to the Strawberry Creek build-out scenario, the modeled release rate for new development in the lower subbasin changes from 0.05 to 0.03 cfs/acre and the detained volume of stormwater runoff increases from 25.0 to 28.6 acre-feet, Figure 12. The 24-hour extended detention criterion reduces both peak flow and the duration of higher flows in Strawberry Creek as shown in Figure 13.

- Peak flow in Strawberry Creek at its mouth is reduced from 77 to 70 cfs, an 11 percent increase from the 2006 rate-controlled scenario instead of 20 percent.
- The duration of erosive flows, defined here as flows that exceed 75 percent of the 2006 rate controlled peak flow, increases 2.2 hours instead of 3.9 hours compared to the peak flow in 2006 rate-controlled scenario, as shown in Figure 13. The reduced duration is possible, even though the same runoff volume is being released, because much of the runoff is released much later at a very low rate, around 5 cfs in this example.

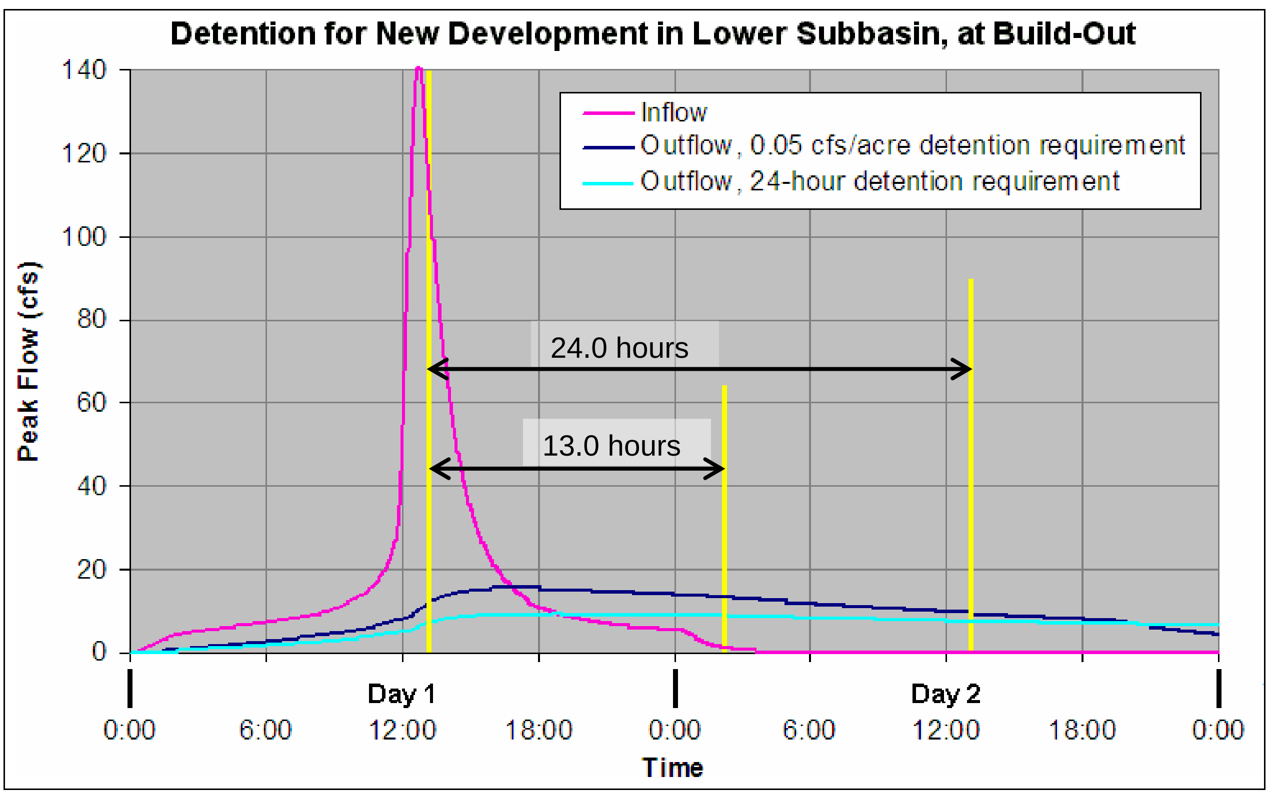

Figure 12: Hydrographs for Rate-Controlled Detention, Build-out Scenario, Lower Watershed, illustrating the change in the hydrographs' centroids (half of the water volume is on each side of the centroid)

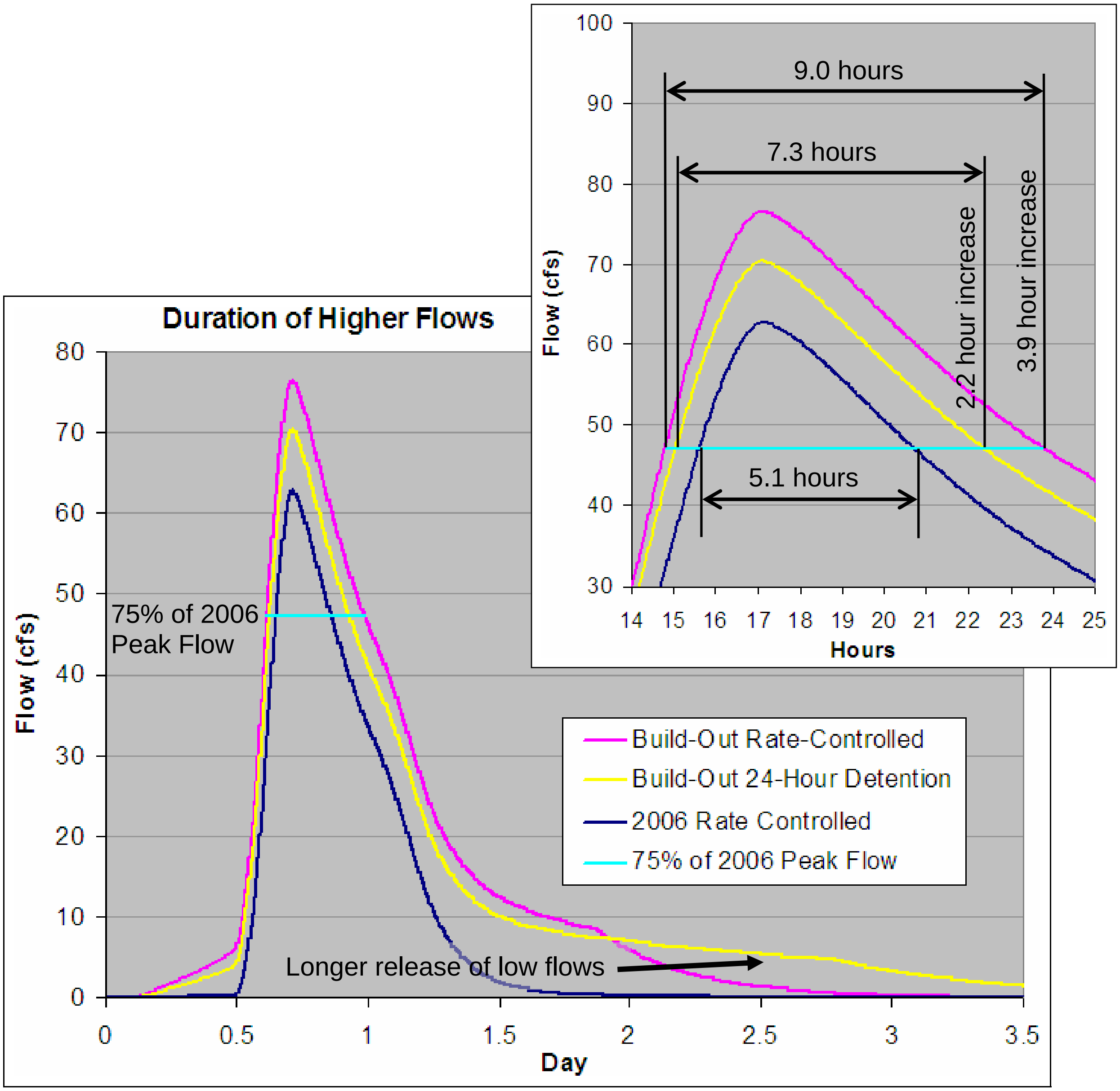

Figure 13: In-stream Hydrographs illustrating the effects of changing from a mandated 0.05 cfs/acre release rate to 24-hour extended detention

Morphologic Analysis

Overview

A stable stream is one that, over time, maintains a stable morphology: a constant pattern (sinuosity), slope, and cross-section, and neither aggrades (fills in) or degrades (erodes). A stable stream is in dynamic equilibrium, defined as "an open system in a steady state in which there is a continuous inflow and output of materials, in which the form or character of the system remains unchanged." (Rosgen, 2006). Stream stability is often depicted as a balance between sediment load, sediment size, stream slope, and stream discharge, Figure 14. The left side of the equation in Figure 14 must always balance the right side. An increase in discharge, for example, increases the sediment-carrying capacity, increases the ability to move larger stone and soil particles, and promotes increased channel meandering and lateral bank erosion as the channel attempts to decrease its slope to restore balance.

Stream stability is not the absence of erosion; some sediment movement and streambank erosion are natural. An unstable stream is characterized by excessive, extensive erosion, with surplus sediment accumulating somewhere downstream, typically near the stream's mouth or in a lake.

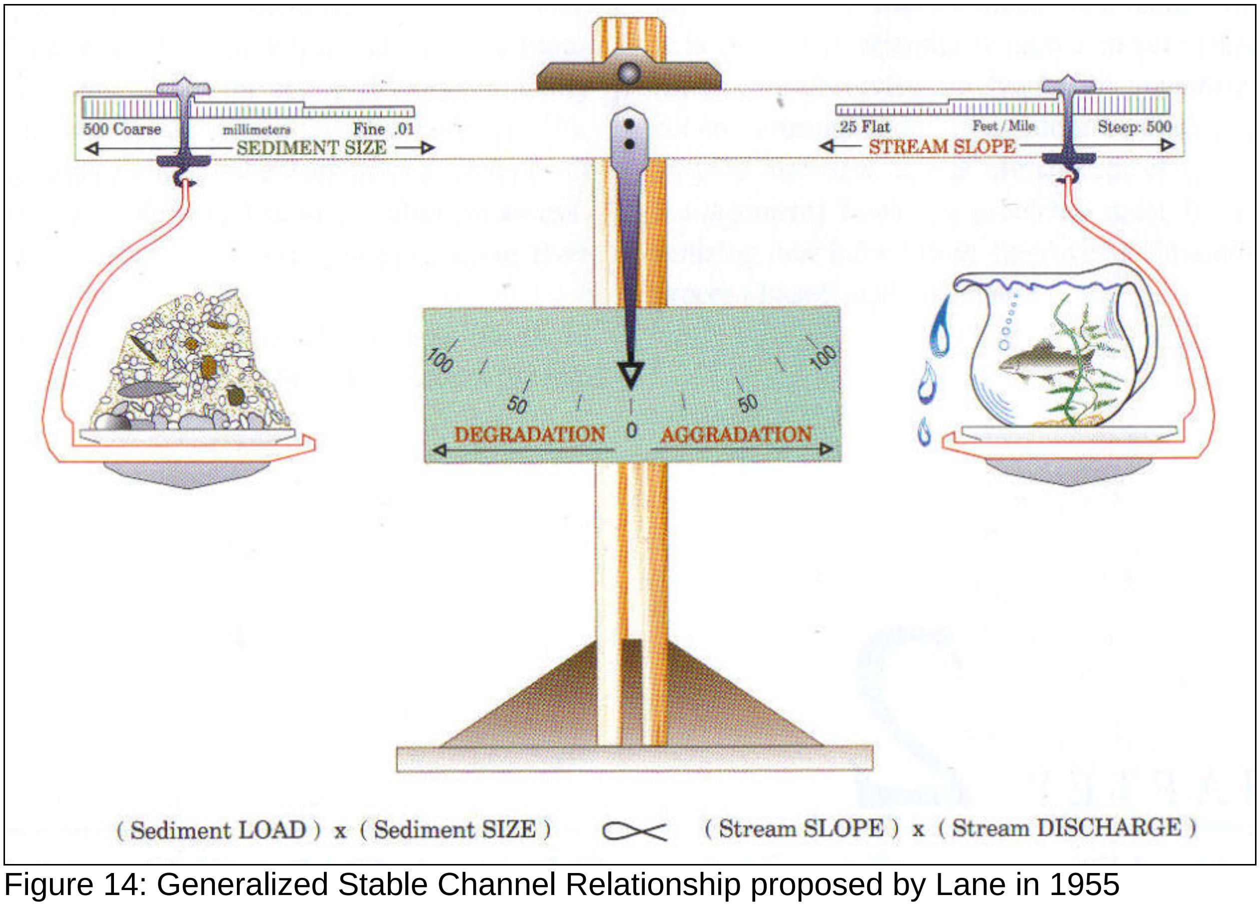

Figure 14: Generalized Stable Channel Relationship proposed by Lane in 1955 (illustration from Rosgen 1996)

Bank Erosion Hazard Index (BEHI) Analysis

MDEQ staff conducted a Bank Erosion Hazard Index (BEHI) analysis at five locations along Strawberry Creek and its tributaries following the BEHI procedure detailed on pages 5-54 through 5-64 in the book "Watershed Assessment of River Stability and Sediment Supply (WARSSS)" (Rosgen, 2006). BEHI is a procedure for evaluating streambank susceptibility to erosion. The five locations are illustrated in Figure 15.

The BEHI analysis indicates that streambank stability is good in the upper watershed but worsens downstream. Sediment has accumulated at the mouth, filling in the pond behind a small dam. Table 8 provides a summary of the BEHI scores. Details for each site follow.

Table 8 – Summary of BEHI scores

Location	BEHI Score	Bank Erosion Hazard
Western tributary near 6 Mile Road	14.0	Low
Eastern tributary near 6 Mile Road	4.5	Very Low
Strawberry Creek near 6 Mile Road	25.1	Moderate
Strawberry Creek in Westgate Park	34.8 – 38.7	High
Strawberry Creek near Stony Creek Road	26.7 – 44.3	Moderate to Very High

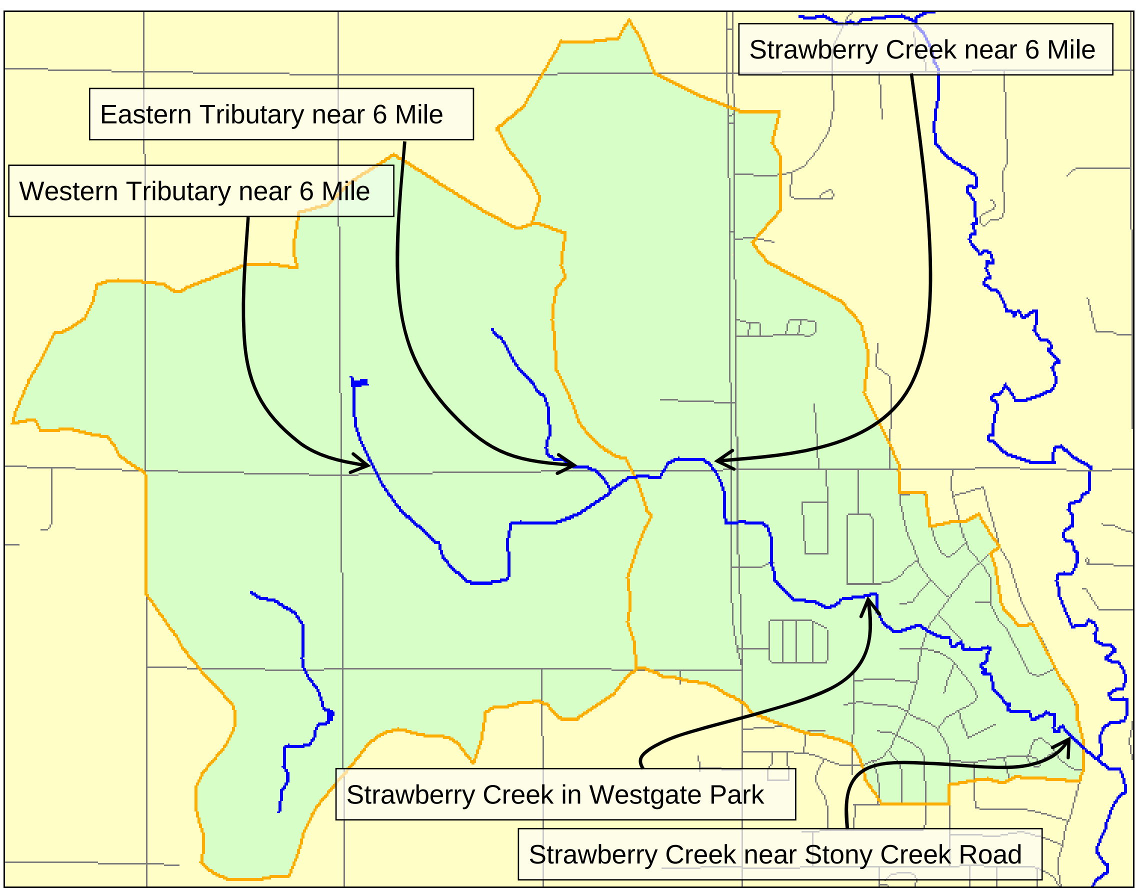

Figure 15 – BEHI site locations

The western tributary near 6 Mile Road, Figure 16, is an incised agricultural drain. It is heavily vegetated and in good condition, with a low bank erosion potential ranking.

Table 9 – BEHI Scoring, Western Tributary near 6 Mile Road

	Value	BEHI score
Bankfull Height = 0.57 feet		
Bank/Bankfull Height	8	10.0
Root Depth	100%	0.0
Root Density	100%	0.0
Bank Angle	60°	4.0
Surface Protection	100%	0.0
Bank Material Adjustment		0.0
Stratification Adjustment		0.0
Total BEHI Score		14.0
Bank Erosion Potential	**Low**	

Figure 16 – Western Tributary near 6 Mile Road: BEHI evaluation site

The eastern tributary near 6 Mile Road, Figure 17, is also an agricultural drain. It is also well vegetated and in good condition, but is not incised, so receives a very low bank erosion potential ranking.

Table 10 – BEHI Scoring, Eastern Tributary near 6 Mile Road

	Value	BEHI score
Bankfull Height 0.79 feet		
Bank/Bankfull Height	1	1.5
Plant Root Depth	100%	0.0
Root Density	100%	0.0
Bank Angle	45°	3.0
Surface Protection	100%	0.0
Bank Material Adjustment		0.0
Stratification Adjustment		0.0
Total BEHI Score		4.5
Bank Erosion Potential	**Very Low**	

Figure 17 – Eastern Tributary near 6 Mile Road: BEHI evaluation site

The condition of Strawberry Creek near 6 Mile Road, near the Alpine Township offices, is more variable than the upstream tributaries. The BEHI scoring is for the reach shown in Figure 18, which is upstream of the township office road crossing. A highly meandering reach just downstream of the crossing, Figure 19, would have a higher bank erosion potential score, but is not considered representative. Figure 20 illustrates another reach, just downstream of Figure 19, bounded by the 6 Mile Road and Alpine Avenue road crossings. This reach would have a lower bank erosion potential score than the reach in Figure 18, due to ponding that may be caused by the road crossing.

Table 11 – BEHI Scoring, Strawberry Creek near 6 Mile Road

	Value	BEHI score
Bankfull Height = 1.46 feet		
Bank/Bankfull Height	1	1.5
Plant Root Depth	85%	2.1
Root Density	10%	9.0
Bank Angle	55°	3.5
Surface Protection	10%	9.0
Bank Material Adjustment		0.0
Stratification Adjustment		0.0
Total BEHI Score		25.1
Bank Erosion Potential	**Moderate**	

Figure 18 – Strawberry Creek near 6 Mile Road: BEHI evaluation site

Figure 19 – Strawberry Creek near 6 Mile Road, downstream of BEHI evaluation site: erosion, typically more pronounced at bends, is not representative of the overall channel

Figure 20 – Strawberry Creek between 6 Mile Road and Alpine Avenue: channel morphology may be influenced by ponding that may be caused by the road crossing and is a marked contrast with the upstream bend erosion in Figure 19

BEHI scoring of Strawberry Creek in Westgate Park indicates a high bank erosion potential. Two riffle sites were analyzed, with similar results, as shown in Table 12. One site is shown in Figure 21. Some stream banks along Strawberry Creek in Westgate Park have been stabilized. The stabilization sites were typically at bends further impacted by foot traffic. A typical site is shown in Figure 22.

Table 12 – BEHI Scoring, Strawberry Creek in Westgate Park

	Site 1		Site 2	
	Value	BEHI score	Value	BEHI score
Bankfull Height = 2.64 feet				
Bank/Bankfull Height	1.5	6.0	1.8	7.3
Plant Root Depth	50%	3.9	90%	1.9
Root Density	10%	8.8	10%	8.8
Bank Angle	90°	8.0	40°	2.8
Surface Protection	20%	7.0	10%	9.0
Bank Material Adjustment		5.0		5.0
Stratification Adjustment		0.0		0.0
Total BEHI Score		38.7		34.8
Bank Erosion Potential	**High**		**High**	

Figure 21 – Strawberry Creek in Westgate Park: BEHI evaluation site

Figure 22 – Strawberry Creek in Westgate Park: bank stabilization site

Bankfull indicators and BEHI scoring for Strawberry Creek near Stony Creek Road were the most varied. The stream's morphology is not stable, and the bankfull indicators are therefore the least reliable. Three sites were analyzed, as shown in Table 12. One site is shown in Figure 23. Figure 24 illustrates an attempt to stabilize erosion at a bend. Figure 25 illustrates a high bank being undercut. A small dam, Figure 29, has filled in with sediment from the eroding banks.

Table 13 – BEHI Scoring, Strawberry Creek near Stony Creek Road

	Site 1		Site 2		Site 3	
	Value	BEHI score	Value	BEHI score	Value	BEHI score
Bankfull Height 3.66 feet						
Bank/Bankfull Height	1	1.5	1.1	2.0	3.5	10
Plant Root Depth	70%	3.0	90%	1.9	75%	2.8
Root Density	35%	5.2	15%	8.0	25%	6.5
Bank Angle	100°	8.5	90°	8.0	100°	8.5
Surface Protection	60%	3.5	15%	8.0	25%	6.5
Bank Material Adjustment		5.0		5.0		5.0
Stratification Adjustment		0.0		0.0		5.0
Total BEHI Score		26.7		33.9		44.3
Bank Erosion Potential	**Moderate**		**High**		**Very High**	

Figure 23 – Strawberry Creek near Stony Creek Road: BEHI evaluation site

Figure 24 – Strawberry Creek upstream of Stony Creek Road: bank stabilization attempt at an eroding bend


Figure 25 – Strawberry Creek upstream of Stony Creek Road: undercut bank


Figure 26 – Small Dam on Strawberry Creek downstream of Stony Creek Road

Tractive Force Analysis

This tractive force analysis uses a simplified shear stress equation to estimate channel stability. The equation assumes uniform flow in a straight channel with typical hydraulic roughness, which excludes heavily vegetated channels. Bends, local turbulence, and smoother channels can all increase the particle size mobilized above the calculated value. The equation is explained in detail in Appendix D.

Channel stability is estimated by comparing the calculated incipient particle diameter (IPD) that moves at bankfull flow to the measured IPD, as shown in Table 14. The measured IPD is the diameter at which either 50 or 84 percent of the measured channel bed particles are smaller (D_{50} and D_{84}, respectively). Both D_{50} and D_{84} have been used in this method, although D_{84} may be more prevalent. The results for Strawberry Creek are summarized in Table 15 and detailed in Table 16.

The size of the particle that would be mobilized at bankfull flow increases dramatically from 0.38 cm (0.14 inches) at 6 Mile Road to 2.3 cm (0.91 inches) at Westgate Park. This stream power increase is attributable to increases in both slope and bankfull flow.

The tractive force analysis correlates with the BEHI analysis. Strawberry Creek near Stony Creek Road had the highest BEHI score, very high bank erosion potential, and the largest difference between calculated and measured stream bed IPD. Strawberry Creek near 6 Mile Road, although still indicating a significant difference between calculated and measured stream bed IPD, has less power and a lower BEHI score, with moderate bank erosion potential. Strawberry Creek at Westgate Park may have a channel bottom resistant to excessive erosion at current flows, but according to the BEHI analysis, the banks remain at high risk of erosion.

Table 14 – Interpretation of Tractive Force Analysis

Calculated IPD << Measured IPD	Potential Deposition
Calculated IPD ≈ Measured IPD	Approximate Equilibrium
Calculated IPD >> Measured IPD	Potential Erosion

Table 15 – Tractive Force Analysis at Three Strawberry Creek Sites

Strawberry Creek Location	Incipient Particle Diameter (cm)		Estimated Channel Stability
	Calculated	Measured	
near 6 Mile Road	0.38	0.025 – 0.050	Potential Erosion
at Westgate Park	2.3	0.82 – 1.9	Approximate Equilibrium*
near Stony Creek Road	2.4	0.025 – 0.050	Potential Erosion

*The NPS program is initially using calculated IPD/measured D_{84} IPD > 1.7 as an indicator of potential erosion. If D_{50} is used, the estimated channel stability at Westgate Park would change to Potential Erosion.

Table 16 – Tractive Force Analysis Details

Location	Tractive Force – Calculated IPD	Bed Material – Measured IPD
Strawberry Creek near 6 Mile Road	Slope = 0.00086 Bankfull Depth = 1.46 ft x 305cm/ft = 445 mm IPD (cm) = BFdepth (mm) x Slope = 0.38 cm	Medium Sand 0.025 – 0.050 cm
Strawberry Creek at Westgate Park	Slope = 0.00281 Bankfull Depth = 2.64 ft x 305 cm/ft = 805 mm IPD (cm) = BFdepth (mm) x Slope = 2.3 cm	D_{50} = 0.82 cm D_{84} = 1.9 cm
Strawberry Creek near Stony Creek Road	Slope = 0.00211 ft/ft Bankfull Depth = 3.66 ft x 305cm/ft = 1116 mm IPD (cm) = BFdepth (mm) x Slope = 2.4 cm	Medium Sand 0.025 – 0.05 cm

Channel Evolution

The hydrologic analysis indicates peak flows have been increasing and will continue to do so into the future. BEHI analysis indicates moderate to very high bank erosion potential below approximately 6 Mile Road and Alpine Avenue. Tractive Force analysis indicates that stream power exceeds the resistance of most of the channel bed material, also indicating potential erosion. The stream channel is evolving to adapt to the higher flow regime. Simon (1989) defined six stages of channel evolution, Table 17. The stages describe a stream's erosive evolution, starting with a stable channel (stage I) and ending with a refilled channel (stage VI). In between, the stream is disturbed by urbanization, forest clearing, dam construction, etc.

Table 17 – Stages of Channel Evolution

Stage	Stream Condition
I	Stream is stable.
II	Watershed's hydrologic characteristics change – forest clearing, urbanization, dam construction, channel dredging, etc.
III	Channel instability sets in with scouring of the bed.
IV	Bank erosion and channel widening occur.
V	Banks continue to cave into the stream, widening the channel. The stream also accumulates sediment from upstream erosion.
VI	Re-equilibrium occurs and bank erosion ceases. Riparian vegetation becomes established.

Strawberry Creek near 6 Mile Road is most likely at stage I (or VI if the time frame is since 1800), since the flow changes due to urbanization are occurring downstream. Strawberry Creek at Westgate Park may be at stage IV. The bed is scoured and the channel is widening. Strawberry Creek near Stony Creek Road may be at Stage V, widening but also accumulating sediment from upstream. The stages are uncertain because the lower Strawberry Creek is simultaneously at stage 2, with projected land use changes expected to further increase channel-forming flows, even with the 0.05 cfs/acre release rate controls.

To handle the modeled 1978, 2006, and build-out flow increases, the channel cross-sectional area must also increase to provide more capacity. Estimates of channel cross-sections are shown in Figure 27, superimposed on a photo of the channel near Stony Creek Road. The build-out flow with no rate control is provided for comparison. These cross-sections were developed using hydraulic analysis software, HEC-RAS 3.1.3. The cross-section areas are detailed in Table 18.

Table 18 – Model Cross-Sections

Scenario	Flow	Cross-Section Area
1978	53	25
2006, 0.05 cfs/acre rate control	63	30
Build-out, 0.05 cfs/acre rate control	77	35
Build-out, no rate control	117	48

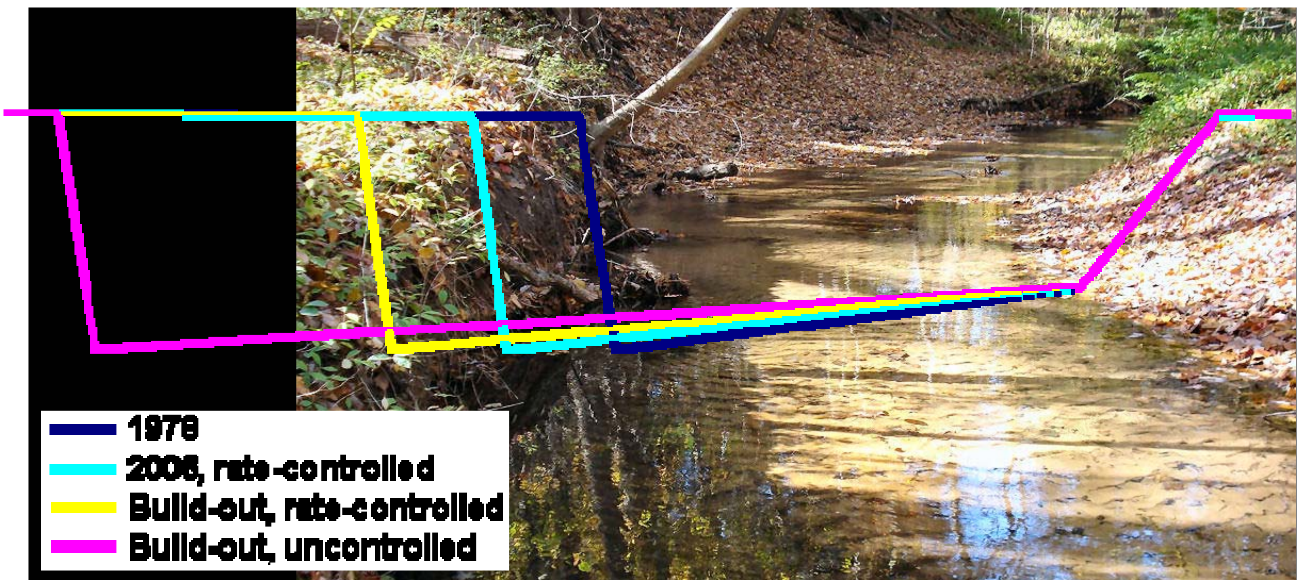

Figure 27 – Potential Channel Cross-sections

Recommendations

The higher flows, and the longer duration of higher flows because of the increased runoff volumes, are destabilizing the stream channel and will continue to do so unless stormwater management in the watershed is improved. The 0.05 cfs per acre standard in the stormwater management ordinance serves to reduce destabilizing peak flows and reduce at least some of the increased runoff volume to non-erosive velocities. Unless the increased runoff can be infiltrated, extended duration of higher flows is unavoidable. Refinements to the stormwater ordinance would better protect Strawberry Creek. These refinements could include 24-hour extended detention of runoff from 1-year storms or provision for retention and infiltration of additional stormwater runoff through Low Impact Development (LID) practices, as discussed further in the following Stormwater Management, Stream Channel Protection section of this report.

Stormwater Management

When precipitation falls, it can infiltrate into the ground, evapotranspirate back into the air, or run off the ground surface to a water body. It is helpful to consider three principal runoff effects: water quality, channel shape, and flood levels, as shown in Figure 28.

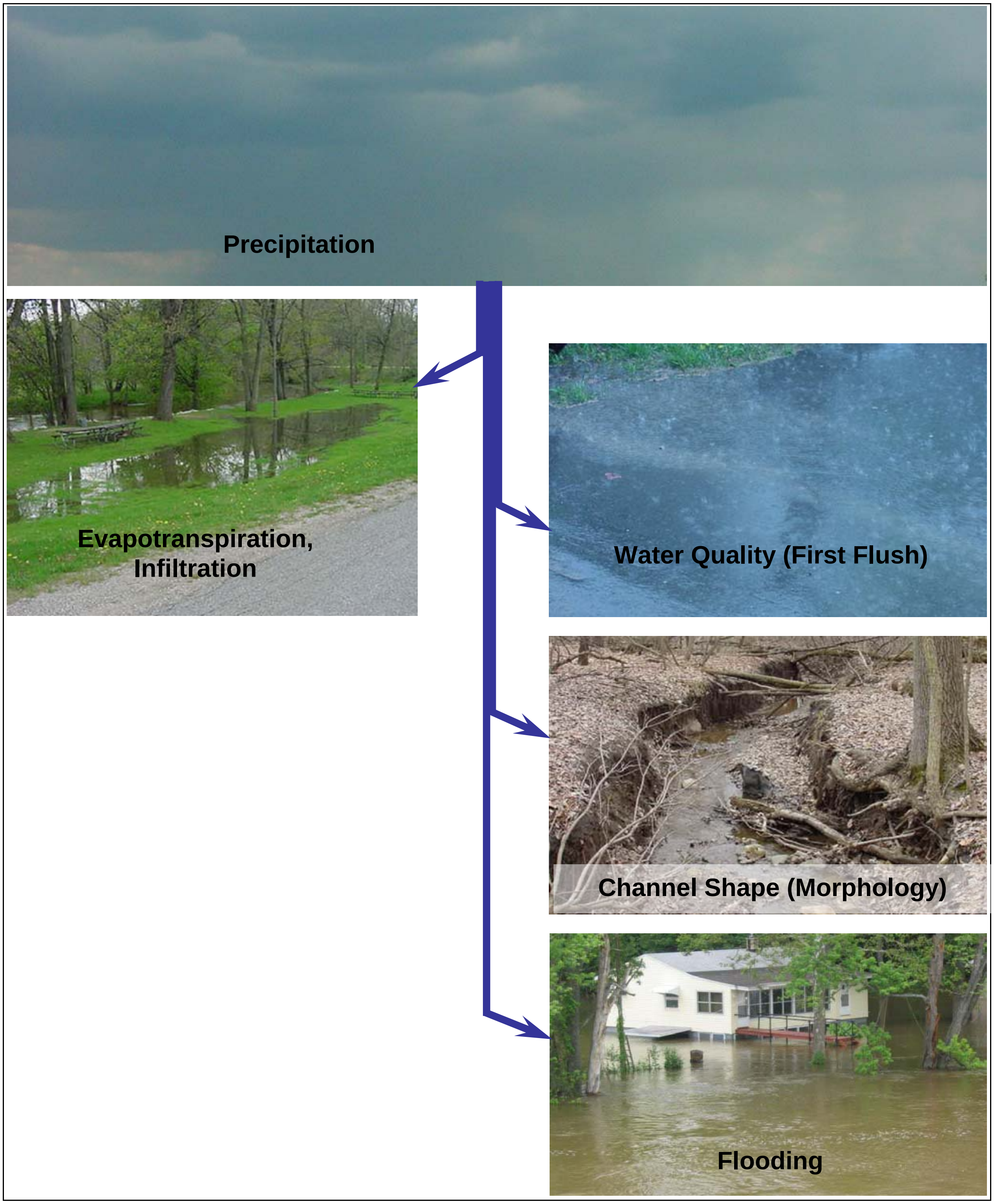

Figure 28: Runoff Impacts

Land use changes that reduce evapotranspiration and infiltration increase runoff. One reason low impact development has become more popular is that it avoids creating more runoff; intercepting and infiltrating the excess runoff instead.

Runoff from small rainfall events and the first portion of the runoff from larger events is termed the “first flush”, because it carries the majority of the pollutants. For more information, refer to the Water Quality section.

Larger, but frequent, storms or snowmelts produce the flows that shape the channel. These relatively modest storm flows, because of their higher frequency, have more effect on channel form than extreme flood flows. Hydrologic changes that increase this flow can cause the stream channel to become unstable. Stormwater management techniques used to mitigate flooding can also help mitigate projected channel-forming flow increases. However, channel-forming flow criteria should be specifically considered in the stormwater management plan so that the selected BMPs will be most effective. For example, detention ponds designed to control runoff from the 4 percent chance, 24-hour storm may do little to control the runoff from the 50 percent chance, 24-hour storm, unless the outlet is specifically designed to do so. For more information, refer to the Stream Channel Protection section.

Increases in the runoff volume and peak flow from large storms, such as the 4 percent chance (25-year), 24-hour storm, could cause or aggravate flooding problems unless mitigated using effective stormwater management techniques. For more information, refer to the Flood Protection section.

Water Quality

Small runoff events and the first portion of the runoff from larger events typically pick up and deliver the majority of the pollutants to a watercourse in an urban area (Menerey, 1999 and Schueler, 2000). As the rain continues, there are fewer pollutants available to be carried by the runoff, and thus the pollutant concentration becomes lower. Figure 29 shows a typical plot of pollutant concentration versus time. The sharp rise in the plot has been termed the "first-flush." Some of the pollutants can settle out before discharging to a stream if this first flush runoff is detained for a period of time. Filtering systems are also used at some sites to treat the first flush stormwater.

Nationally, the amount of runoff recommended for capture and treatment varies from 0.5 inch per impervious acre to the runoff from a 50 percent chance storm. Michigan BMP guidelines recommend capture and treatment of 0.5 inches of runoff from a single site (Guidebook of Best Management Practices for Michigan Watersheds, 1998). The runoff is then released over 24 to 48 hours or is allowed to infiltrate into the ground within 72 hours. Dry detention ponds are less effective than retention or wet detention ponds, because the accumulated sediment in a dry detention pond may be easily resuspended by the next storm (Schueler, 2000).

Runoff from multiple or large sites may exhibit elevated pollutant concentrations longer because the first flush runoff from some portions of the drainage area will take longer to reach the outlet. For multiple sites or watershed wide design, it is best to design to capture and treat 90 percent of runoff-producing storms. This "90 percent rule" effectively treats storm runoff that could be reaching the treatment at different times during the storm event. It was designed to provide the greatest amount of treatment that is economically feasible. In Michigan, values calculated for these storms range from 0.77 to 1.00 inches. For the Strawberry Creek watershed climatic regions, the calculated value is 0.93 inches. Additional information is available at www.michigan.gov/documents/deq/lwm-hsu-nps-ninety-percent_198401_7.pdf.

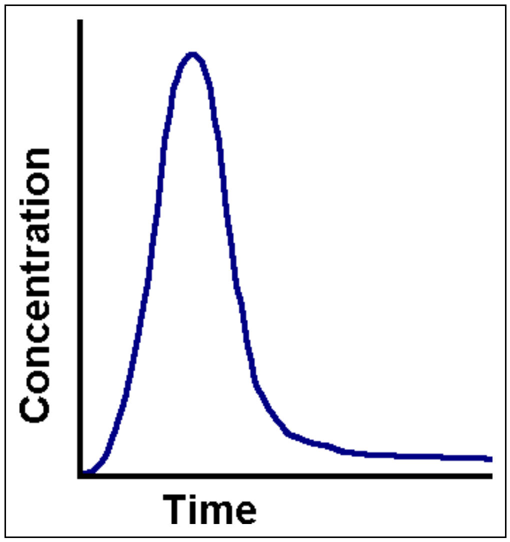

Figure 29: Plot of Pollutant Concentration versus Time

Stream Channel Protection

A stable stream is one that, over time, maintains a stable morphology: a constant pattern (sinuosity), slope, and cross-section, and neither aggrades or degrades. Stream stability is not the absence of erosion; some sediment movement and streambank erosion are natural.

Possible causes of erosion are:

- Natural river dynamics
- Sparse vegetative cover due to too much animal or human traffic
- Concentrated runoff adjacent to the streambank, i.e. gullies, seepage
- In-stream flow obstructions, i.e. log jams, failed bridge supports
- An infrequent event, such as an ice jam or low probability flood
- Unusually large or frequent wave action
- A significant change in the hydrologic characteristics (typically land use) of the watershed
- A change in the stream form impacting adjacent portions of the stream, i.e. dredging, channelization

An assessment of the cause(s) of erosion is necessary so that proposed solutions will be permanent and do not simply move the erosion problem to another location. The first six listed causes can produce localized erosion. Either of the last two causes, however, could produce a morphologically unstable stream. Symptoms of active channel enlargement in an unstable stream include:

- Down-cutting of the channel bottom
- Extensive and excessive erosion of the stream banks
- Erosion on the inside bank of channel bends
- Evidence in the streambanks of bed erosion down through an armor layer
- Exposed sanitary or storm sewers that were initially installed under the steam bed

Erosion in a morphologically unstable stream is caused by increases in the relatively frequent channel-forming flows that, because of their higher frequency, have more effect on channel form than extreme flood flows. As shown in Figure 30, multiplying the sediment transport rate curve (a) by the storm frequency of occurrence curve (b) yields a curve (c) that, at its peak, indicates the flow that moves most of the sediment in a stream. This flow is termed the effective discharge. The effective discharge usually has a one- to two-year recurrence interval and is the dominant channel-forming flow in a stable stream.

Increases in the frequency, duration, and magnitude of these flows cause stream bank and bed erosion as the stream adapts. According to the *Stream Corridor Restoration* manual, stream channels can often enlarge their cross-sectional area by a factor of 2 to 5 (FISRWG, 10/1998). In *Dynamics of Urban Stream Channel Enlargement, The Practice of Watershed Protection*, ultimate channel enlargement ratios of up to approximately 10 are reported, as shown in Figure 31 (Schueler and Holland, 2000). To prevent or minimize this erosion, watershed stakeholders should specifically consider stormwater management to protect channel morphology. Low impact development and infiltration BMPs can be incorporated to offset flow increases. Stormwater management ordinances can specifically address channel protection. However, where ordinances have included channel protection criteria, it has typically been focused on controlling peak flows from the 2-year storm.

The nationally recognized Center for Watershed Protection asserts that 24-hour extended detention for runoff from 1-year storms better protects channel morphology than 2-year peak discharge control because it does not reduce the frequency of erosive bankfull and sub-bankfull flows that often increase as development occurs within the watershed. Indeed, it may actually increase the duration of these erosive, channel-forming flows. The intent of 24-hour extended detention for runoff from 1-year storms is to limit detention pond outflows from these storms to non-erosive velocities, as shown in Figure 32. A few watershed plans funded through the MDEQ Nonpoint Source Program have recommended requirements based on this criterion. One such example is from the Anchor Bay Technical Report and is shown in Figure 33. This analysis, which is for climatic region 10, is for 2.06 inches of rainfall. The Strawberry Creek watershed is mostly in climatic region 8, which has a 50 percent chance (2-year) 24-hour storm design rainfall value of 2.37 inches, as tabulated in *Rainfall Frequency Atlas of the Midwest*, Bulletin 71, Midwestern Climate Center, 1992, pp. 126-129. The MDEQ Nonpoint Source Program is funding this analysis for western Michigan through the Lower Grand Initiatives grant, 2007-0137, to the Grand Valley Metropolitan Council.

Detention designed to control channel-forming flows and prevent streambank erosion may not be needed for runoff routed from a city through storm sewers to a large river, such as the Grand River at Comstock Park, simply because the runoff routed through the storm sewers enters the river well ahead of the peak flow in the river. In this case, the management plan for stormwater routed through storm sewers should focus on treating the runoff to maintain water quality and providing sufficient drainage capacity to minimize flooding. Detention/retention might also be encouraged or required for other reasons, such as water quality improvement, groundwater replenishment, or if watershed planning indicates continued regional development would alter the river's flow regime or increase flood levels.

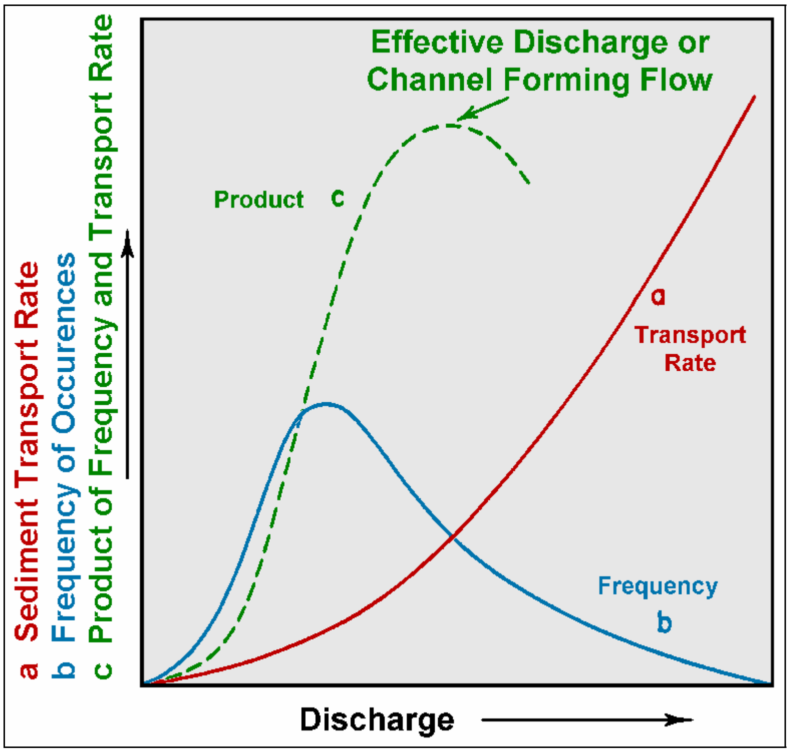

Figure 30: Effective Discharge (from *Applied River Morphology*. 1996. Dave Rosgen)

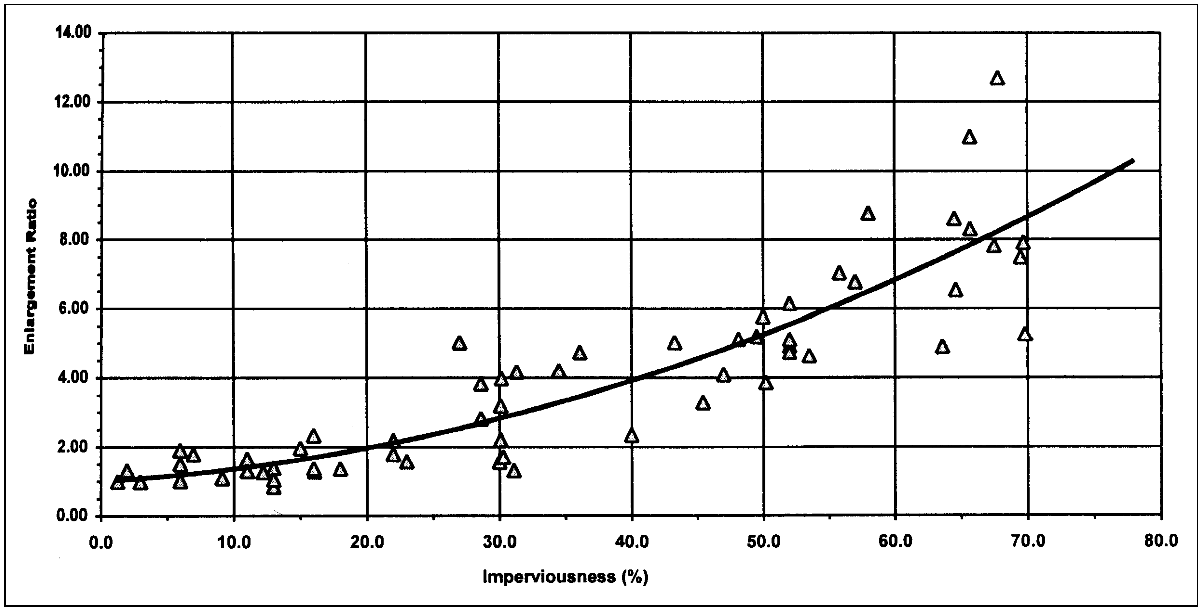

Figure 31: “Ultimate” Channel Enlargement as a Function of Impervious Cover in Alluvial Streams in Maryland, Vermont, and Texas (MacRae and DeAndrea, 1999; and Brown and Claytor, 2000) (From *The Practice of Watershed Protection*, Thomas R. Schueler and Heather K. Holland, 2000)

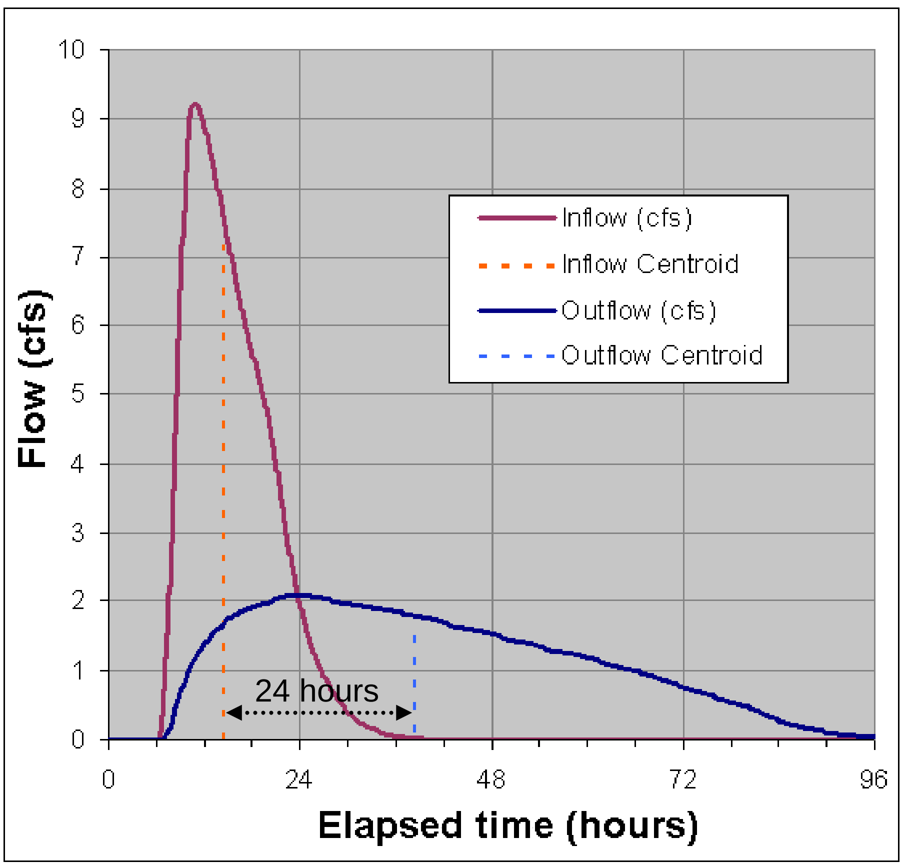

Figure 32: Example of 24-hour extended detention criterion applied to detention pond design

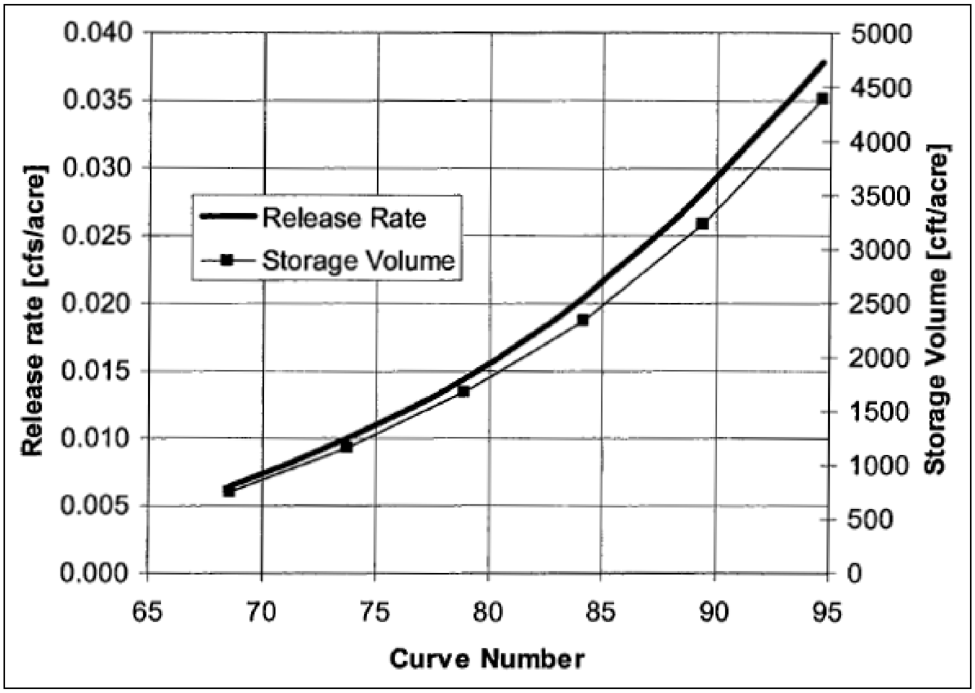

Figure 33: Example of detention pond requirements derived from the 24-hour extended detention criterion

Flood Protection

A river, stream, lake, or drain may occasionally overflow its banks and inundate adjacent land. This land is the floodplain. The floodplain refers to the land inundated by the 1 percent chance flood, commonly called the 100-year flood. Typically, a stable stream will recover naturally from these infrequent events. Developments should always include stormwater controls that prevent flood flows from exceeding pre-development conditions and putting people, homes, and other structures at risk. Many localities require new development to control the 4 percent chance flood, commonly called the 25-year flood, with some adding requirements to control the 1 percent chance flood.

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Appendix A: Strawberry Creek Hydrologic Parameters

The watershed was modeled using HEC-HMS 3.1.0 to calculate surface runoff volumes and peak flows from individual subbasins. This appendix is provided so that the model may be recreated.

Table A1 provides the hydrologic parameters that were specified for each of the subbasin elements in the HEC-HMS model, Figure A-1. The storage coefficient for each subbasin was set equal to the associated time of concentration. Where the percent impervious fields are blank, imperviousness is incorporated in the curve numbers. The initial loss fields in the HEC-HMS model were left blank so that the model uses the standard equation based on the curve number.

Table A2 provides the hydrologic parameters that were specified for the reservoirs that simulate the 0.05 cfs/acre rate control specified in the local stormwater ordinance.

Table A3 provides the hydrologic parameters that were specified for the reach routing.

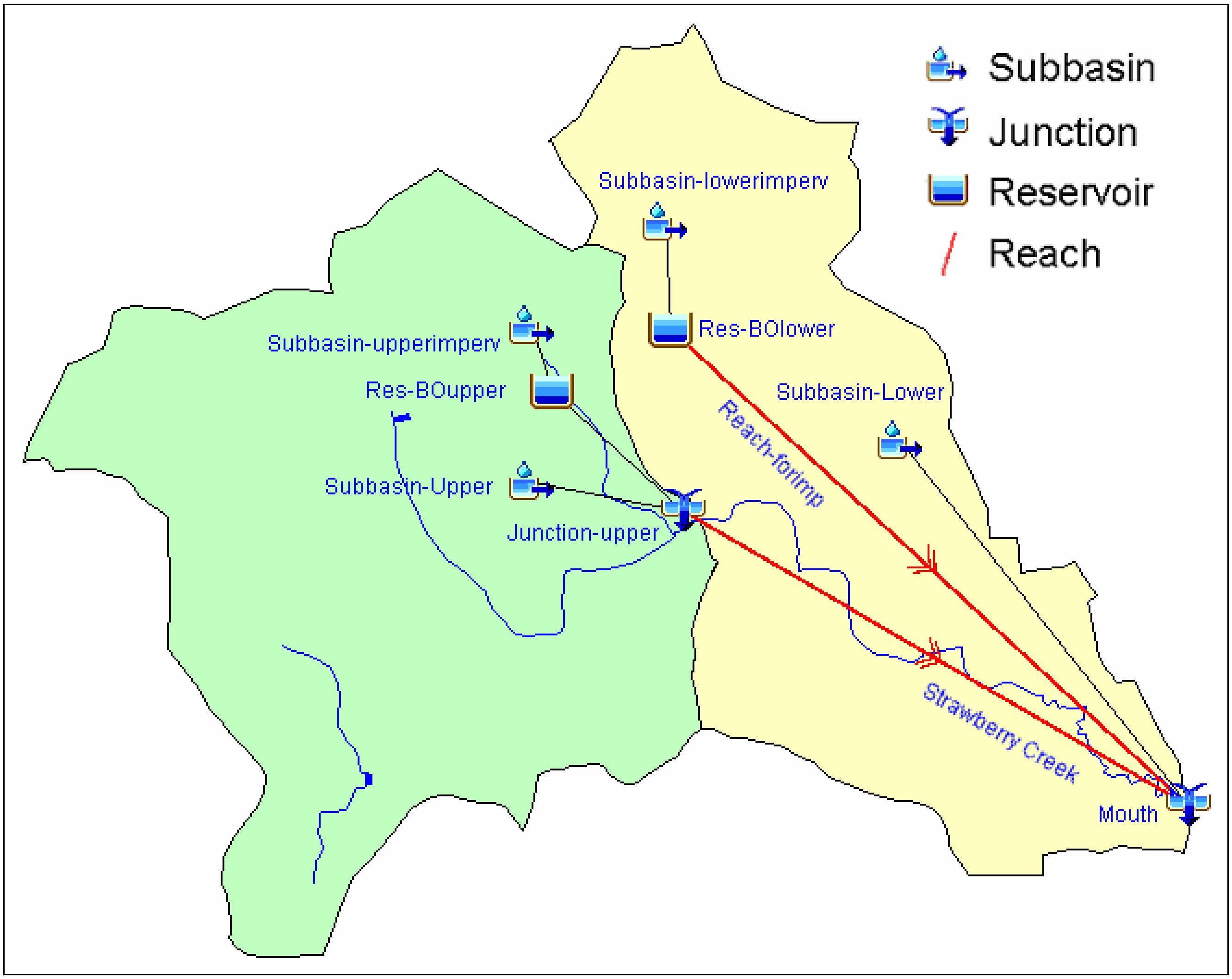

Figure A-1: HMS Hydrologic Model Overview, Build-Out with Rate Control Scenario shown

Table A1: Subbasin Parameters – Drainage Area and Curve Number

Scenario	Subbasin	Drainage Area (sq. mi.)	Curve Number	Impervious Percent	Time of Concentration and Storage Coefficient
A. 1800	Upper	1.63	59.3		3.46
	Lower	1.35	54.5		3.04
B. 1978	Upper	1.63	70.0		3.46
	Lower	1.35	65.8		3.04
C. 2006 RC	Upper	1.63	70.0		3.46
	Lower	1.33	65.5		3.04
	Lower Imperv.	0.02	45.0	72.0%	0.10
D. 2006 no RC	Upper	1.63	70.0		3.46
	Lower	1.35	65.8		3.04
E. Build-out RC	Upper	1.59	69.5		3.46
	Upper Imperv.	0.04	45.0	72.0%	1.00
	Lower	0.87	70.5		3.04
	Lower. Imperv.	0.48	45.0	63.7%	1.00
F. Build-out no RC	Upper	1.63	69.9		3.46
	Lower	1.35	74.6		3.04

Table A2: Reservoir Storage Parameters

Reservoir	Storage (acre-feet)	Discharge (cfs)
Res-2006 Lower	0.0	0.0
	0.25	0.31
	1.25	0.62
Res- Build-out Upper	0.0	0.0
	0.48	0.68
	2.40	1.35
Res- Build-out Lower	0.0	0.0
	5.0	7.67
	24.98	15.33

Table A3: Reach Routing Parameters

Reach	Method	Lag (minutes)	Comments
Strawberry Creek	Lag	101	Parameter value calculated based on Strawberry Creek's length and slope from upper watershed to mouth.
Reach-for Imperv. Area	Lag	101	Reach added to account for travel time from new development located mostly in the upper portion of lower watershed through unknown length of storm drain and open channel. The model results are not sensitive to this parameter's value.

Appendix B: Glossary

Aggrade - to fill and raise the level of a stream bed by deposition of sediment.

Alluvium - sediment deposited by flowing rivers and consisting of sands and gravels.

Bankfull discharge - that discharge of stream water that just begins to overflow in the active floodplain. The active floodplain is defined as a flat area adjacent to the channel constructed by the river and overflowed by the river at recurrence interval of about 2 years or less. Erosion, sediment transport, and bar building by deposition are most active at discharges near bankfull. The effectiveness of higher flows, called over bank or flood flows, does not increase proportionally to their volume above bankfull in a stable stream, because overflow into the floodplain distributes the energy of the stream over a greater area. See also channel-forming and effective discharge.

Base Flow - the part of stream flow that is attributable to long-term discharge of groundwater to the stream. This part of stream flow is not attributable to short-term surface runoff, precipitation, or snow melt events.

Best Management Practice (BMP) - structural, vegetative, or managerial practices used to protect and improve our surface waters and groundwaters.

Channel-forming Discharge - a theoretical discharge which would result in a channel morphology close to the existing channel. See also effective and bankfull discharge.

Critical Areas - the geographic portions of the watershed contributing the majority of the pollutants and having significant impacts on the waterbody.

Critical Depth - depth of water for which specific energy is a minimum.

Curve Number - see Runoff Curve Number.

Design Flow - projected flow through a watercourse which will recur with a stated frequency. The projected flow for a given frequency is calculated using statistical analysis of peak flow data or using hydrologic analysis techniques.

Detention - practices which store stormwater for some period of time before releasing it to a surface waterbody. See also retention.

Dimensionless Hydrograph - a general hydrograph developed from many unit hydrographs, used in the Soil Conservation Service method.

Direct Runoff Hydrograph - graph of direct runoff (rainfall minus losses) versus time.

Discharge - volume of water moving down a channel per unit time. See also channel-forming, effective, and bankfull discharge.

Drainage Divide - boundary that separates subbasin areas according to direction of runoff.

Effective Discharge - the calculated measure of channel forming discharge. This calculation requires long-term water and sediment measurements, although modeling results are sometimes substituted. See also channel-forming and bankfull discharge.

Ephemeral Stream - a stream that flows only during or immediately after periods of precipitation. See also intermittent and perennial streams.

Evapotranspiration - the combined process of evaporation and transpiration.

First Flush - the first part of a rainstorm that washes off the majority of pollutants from a site. The concept of first flush treatment applies only to a single site, even if just a few acres, because of timing of the runoff. Runoff from multiple or large sites may exhibit elevated pollutant concentrations longer because the first flush runoff from some portions of the drainage area will take longer to reach the outlet.

Flashiness - has no set definition but is associated with the rate of change of flow. Flashy streams have more rapid flow changes.

Flood Hazard Zone - area that will flood with a given probability.

Groundwater - that part of the subsurface water that is in the saturated zone.

Headwater Stream - the system of wetlands, swales, and small channels that mark the beginnings of most watersheds.

Hydraulic Analysis - an evaluation of water elevation for a given flow based on channel attributes such as slope, cross-section, and vegetation.

Hydrograph - graph of discharge versus time.

Hydrologic Analysis - an evaluation of the relationship between stream flow and the various components of the hydrologic cycle. The study can be as simple as determining the watershed size and average stream flow, or as complicated as developing a computer model to determine the relationship between peak flows and watershed characteristics, such as land use, soil type, slope, rainfall amounts, detention areas, and watershed size.

Hydrologic Cycle - When precipitation falls to the earth, it may:

- be intercepted by vegetation, never reaching the ground.
- infiltrate into the ground, be taken up by vegetation, and evapotranspirated back to the atmosphere.
- enter the groundwater system and eventually flow back to a surface water body.
- runoff over the ground surface, filling in depressions.
- enter directly into a surface waterbody, such as a lake, stream, or ocean.

When water evaporates from lakes, streams, and oceans and is re-introduced to the atmosphere, the hydrologic cycle starts over again.

Hydrology - the occurrence, distribution, and movement of water both on and under the earth's surface. It can be described as the study of the hydrologic cycle.

Hyetograph - graph of rainfall intensity versus time.

Impervious - a surface through which little or no water will move. Impervious areas include paved parking lots and roof tops.

Infiltration Capacity - rate at which water can enter soil with excess water on the surface.

Interflow - flow of water through the upper soil layers to a ditch, stream, etc.

Intermittent Stream - a stream that flows only during certain times of the year. Seasonal flow in an intermittent stream usually lasts longer than 30 days per year. See also ephemeral and perennial streams.

Invert - bottom of a channel or pipe.

Knickpoint - a point of abrupt change in bed slope. If the streambed is made of erodible material, the knickpoint, or downcut, may migrate upstream along the channel and have undesirable effects, such as undermining bridge piers and other manmade structures.

Lag Time - time from the center of mass of the rainfall to the peak of the hydrograph.

Low Impact Development (LID) - a comprehensive design and development technique that strives to mimic pre-development hydrologic characteristics and water quality with a series of small-scale distributed structural and non-structural controls.

Losses - rainfall that does not runoff, i.e. rainfall that infiltrates into the ground or is held in ponds or on leaves, etc.

Low Flow - minimum flow through a watercourse which will recur with a stated frequency. The minimum flow for a given frequency may be based on measured data, calculated using statistical analysis of low flow data, or calculated using hydrologic analysis techniques. Projected low flows are used to evaluate the impact of discharges on water quality. They are, for example, used in the calculation of industrial discharge permit requirements.

Morphology, Fluvial - the study of the form and structure of a river, stream, or drain.

Nonpoint Source Pollution - pollutants carried in runoff characterized by multiple discharge points. Point sources emanate from a single point, generally a pipe.

Overland Flow - see Runoff.

Peak Flow - maximum flow through a watercourse which will recur with a stated frequency. The maximum flow for a given frequency may be based on measured data, calculated using statistical analysis of peak flow data, or calculated using hydrologic analysis techniques. Projected peak flows are used in the design of culverts, bridges, and dam spillways.

Perched Ground Water - unconfined groundwater separated from an underlying body of groundwater by an unsaturated zone.

Perennial Stream - a stream that flows continuously during both wet and dry times. See also ephemeral and intermittent streams.

Precipitation - water that falls to earth in the form of rain, snow, hail, or sleet.

Rating Curve - relationship between depth and amount of flow in a channel.

Recession Curve - portion of the hydrograph where runoff is from base flow.

Retention - practices which capture stormwater and release it slowly though infiltration into the ground. See also detention.

Riparian - pertaining to the bank of a river, pond, or small lake.

Runoff - flow of water across the land surface as surface runoff or interflow. The volume is equal to the total rainfall minus losses.

Runoff Coefficient - ratio of runoff to precipitation.

Runoff Curve Number - parameter developed by the Natural Resources Conservation Service (NRCS) that accounts for soil type and land use.

Saturated Zone - (1) those parts of the earth's crust in which all voids are filled with water under pressure greater than atmospheric; (2) that part of the earth's crust beneath the regional water table in which all voids, large and small, are filled with water under pressure greater than atmospheric; (3) that part of the earth's crust beneath the regional water table in which all voids, large and small, are ideally filled with water under pressure greater than atmospheric.

Scarp - the sloped bank of a stream channel.

Sediment - soil fragmental material that originates from weathering of rocks and is transported or deposited by air, water, or ice.

Sinuosity - the ratio of stream length between two points divided by the valley length between the same two points.

Simulation Model - model describing the reaction of a watershed to a storm using numerous equations.

Soil - unconsolidated earthy materials which are capable of supporting plants. The lower limit is normally the lower limit of biological activity, which generally coincides with the common rooting of native perennial plants.

Soil Moisture Storage - volume of water held in the soil.

Storage Delay Constant - parameter that accounts for lagging of the peak flow through a channel segment.

Storage-Discharge Relation - values that relate storage in the system to outflow from the system.

Stream Corridor - generally consists of the stream channel, floodplain, and transitional upland fringe.

Subbasins - hydrologic divisions of a watershed that are relatively homogenous.

Synthetic Design Storm - rainfall hyetograph obtained through statistical means.

Synthetic Unit Hydrograph - unit hydrograph for ungaged basins based on theoretical or empirical methods

Thalweg - the "channel within the channel" that carries water during low-flow conditions.

Time of Concentration - time at which outflow from a basin is equal to inflow or time of equilibrium.

Transpiration - conversion of liquid water to water vapor through plant tissue.

Tributary - a river or stream that flows into a larger river or stream.

Unit Hydrograph - graph of runoff versus time produced by a unit rainfall over a given duration.

Unsaturated Zone - the zone between the land surface and the water table which may include the capillary fringe. Water in this zone is generally under less than atmospheric pressure, and some of the voids may contain air or other gases at atmospheric pressure. Beneath flooded areas or in perched water bodies, the water pressure locally may be greater than atmospheric.

Vadose Zone - see Unsaturated Zone.

Watershed - area of land that drains to a single outlet and is separated from other watersheds by a divide.

Watershed Delineation - determination of watershed boundaries. These boundaries are determined by reviewing USGS quadrangle maps. Surface runoff from precipitation falling anywhere within these boundaries will flow to the waterbody.

Water Surface Profile - plot of the depth of water in a channel along the length of the channel.

Water Table - the surface of a groundwater body at which the water pressure equals atmospheric pressure. Earth material below the groundwater table is saturated with water.

Yield (Flood Flow) - peak flow divided by drainage area

Appendix C: Abbreviations

BEHI	Bank Erosion Hazard Index
CN	Runoff Curve Number
cfs/acre	cubic feet per second per acre
EPA	United States Environmental Protection Agency
GIS	Geographic Information Systems
HSU	MDEQ's Hydrologic Studies Unit
IPD	Incipient Particle Diameter
LID	Low Impact Development
LWMD	MDEQ's Land and Water Management Division
MDEQ	Michigan Department of Environmental Quality
NPS	Nonpoint Source
NRCS	Natural Resources Conservation Service
P/S	Ratio of precipitation, P, to potential maximum retention, S

Appendix D: Modified Tractive Force Equation Derivation

The modified tractive force equation is best used as a screening tool to estimate the particle size on the channel bottom that will likely be moved by the water flowing above it.

$$d_p = D_w S$$

where

d_p is particle diameter mobilized in mm
D_w is the channel depth in cm
S is channel slope in m/m or ft/ft

Although it has inconsistent units, its units were actually selected to provide an unstated conversion factor of one. It is derived from two fundamental shear stress equations as described below. The stress equations are from different scales of analysis: one is a point analysis on a sediment particle, the other a channel scale analysis on the channel's bed. For this derivation, the point analysis is assumed typical of the entire channel, recognizing that in real streams, stresses at points across a channel will vary with local conditions.

Shear stress on the bed material caused by the flowing water can be calculated using the boundary shear stress equation, below, for uniform flow in a straight, open channel. The boundary shear stress equation for meanders is described in the box to the right for reference, but is not used in this derivation.

$$\tau_o = \gamma_w RS$$

where,

τ_o is boundary shear stress in N/m^2
γ_w is the density of water in N/m^3
R is hydraulic radius of the channel in m
S is channel slope in m/m or ft/ft

> If the channel curves, the shear stress will be higher on the outside of the bend than the inside. The equation becomes:
>
> $$\tau_o = \gamma_w RS(R_c/B)$$
>
> where
> R_c is radius of curvature in m or feet
> B is bottom width in consistent units
>
> Typical values of R_c/B are
> Straight reach 1.0
> Mild meanders 1.1 to 1.4
> Looping meanders 1.5 to 1.8
> Sharp turns 1.9 to 2.1

Incipient mobilization, or entrainment, of sediment particles can be calculated with the Shields critical shear equation:

$$\tau_{cr} = \Theta g(\rho_p - \rho_w)d_p$$

where,

τ_{cr} is boundary shear stress at the threshold of entrainment in N/m^2
Θ is a dimensionless shear parameter
g is the acceleration due to gravity m/sec^2
ρ_p is the density of the sediment particle in kg/m^3
$\rho\omega$ is the density of water in kg/m^3
d_p is particle diameter in m

Setting $\tau_o = \tau_{cr}$ results in:

$$\Theta g(\rho_p - \rho_w)d_p = \gamma_w RS$$

Assuming γ_w = 9,800 N/m^3, g = 9.8 m/sec^2, ρ_p = 2,650 kg/m^3 and ρ_w = 1,000 kg/m^3, the equation becomes:

$$(\Theta)(9.8 \text{ m/sec}^2)(1650 \text{ kg/m}^3)(d_p \text{ m}) = (9800 \text{ kg/m}^2\text{sec}^2)(R \text{ m})(S)$$

For hydraulically rough channels, Θ is most often estimated as 0.06, but varies with hydraulic roughness, Table D-1. For hydraulically smooth channels, Θ is much higher: 0.8-3.0.

Table D-1

Channel	Θ
Normal beds: “settled” bed with uniform or random arrangement of grain sizes	0.035-0.065
Loose beds: quick sands and gravels with large water-filled voids	0.01-0.035
Packed beds: smaller material filling voids between larger components	0.065-0.1
Highly embedded with fines	>0.1

(from Carson & Griffiths 1987)

Assuming Θ = 0.06, the equation simplifies to:

$$(9.8 \text{ m/sec}^2)(100 \text{ kg/m}^3)(d_p \text{ m}) = (9800 \text{ kg/m}^2\text{sec}^2)(R \text{ m})(S)$$

$$(980 \text{ kg/m}^2\text{sec}^2)(d_p \text{ m}) = (9800 \text{ kg/m}^2\text{sec}^2)(R \text{ m})(S)$$

$$d_p \text{ m} = 10 \text{ (R m) (S)}$$

In wide channels, R can be approximated by the water depth, D_w. In narrow, deep channels, R will be less than D_w. Figure D-1 illustrates the error for a rectangular channel.

$$d_p \text{ m} = 10 \text{ (}D_w \text{ m) (S)}$$

when d_p is expressed in cm and D_w in mm, the equation becomes:

$$d_p \text{ mm} = (D_w \text{ cm) (S)}$$

In summary, this simplification applies to uniform flow in a straight channel with hydraulic roughness conforming to the assumption that the dimensionless shear parameter is approximately 0.06. Bends, local turbulence, and smoother channels can all increase the particle size mobilized. Rosgen, 2006 has also noted that “in heterogeneous bed materials, larger particles are entrained at shear stress values much lower than indicated” by the Shields critical shear equation. This is detailed on pages 2-8 through 2-10 and 5-139 of ”Watershed Assessment of River Stability and Sediment Supply (WARSSS).”

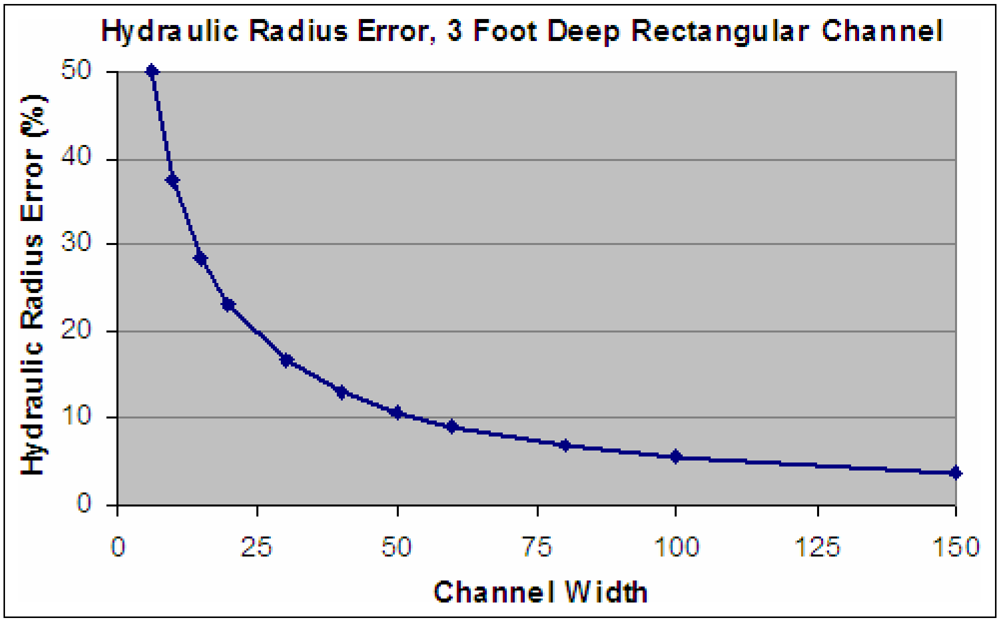

Figure D-1 – Percent error incurred by substituting water depth for hydraulic radius in a rectangular channel